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OFFICE OF RADIATION PROGRAMS TRAINING MANUAL. MANAGEMENT OF RADIATION ACCIDENTS

Environmental Protection Agency
Washington, D. C.

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OFFICE OF RADIATION PROGRAMS

TRAINING MANUAL

MANAGEMENT OF RADIATION ACCIDENTS

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ENVIRONMENTAL PROTECTION AGENCY

229

MANAGEMENT OF RADIATION ACCIDENTS

This course is designed to provide personnel with knowledge of the potential hazards arising from accidents involving radiation and with guidance for the management of these accidents. This manual has been prepared for the trainees attending the course and should not be cited as generally available in reading lists or periodicals.

RADIOLOGICAL HEALTH AND PROTECTION
TRAINING PROGRAM

Western Environmental Research Laboratory
Eastern Environmental Radiation Laboratory

U. S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D. C. 20460

ENVIRONMENTAL PROTECTION AGENCY

On December 2, 1970, President Nixon's Reorganization Plan Number Three of 1970, which created the Environmental Protection Agency, went into effect. This Agency was established as an independent federal agency to make possible an integrated, coordinated attack on pollution, based on a view of the environment as it really is -- a single system of interdependent and interrelated parts, and to serve as an objective, impartial arbiter of environmental matters. Groups concerned with environmental pollution and control, located in various federal agencies, were brought together into the new Environmental Protection Agency.

Part of the functions, responsibilities and personnel of the Bureau of Radiological Health, Public Health Service were reassigned to the Environmental Protection Agency, including portions of the Radiological Health Training Program.

At present, Radiological Health and Protection short-term training is conducted by the Environmental Protection Agency at the Western Environmental Research Laboratory (formerly the Southwestern Radiological Health Laboratory) and the Eastern Environmental Radiation Laboratory (formerly the Southeastern Radiological Health Laboratory). The main emphasis for the training will be related to environmental protection including that for radiation.

The material used in this manual was developed originally by the training staff of the Bureau of Radiological Health, Public Health Service, and is being revised and re-edited, as necessary, by staff members of the Radiation Training Program, Environmental Protection Agency.

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MANAGEMENT OF RADIATION ACCIDENTS

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Sources of Radiation Exposure

1. SOURCES OF RADIATION EXPOSURE

The human race has always been exposed to ionizing radiation of cosmic origin and from natural sources in the environment and within the body. A representative distribution of the dose received from this source is shown in Table 1.(1) The indicated total of 125 millirems per year is an estimated average figure for the United States. The exact amount varies with locality because of differences in the amounts of natural radioactive material present and variation in the intensity of cosmic rays with altitude and latitude. For example, cosmic radiation increases by a factor of 2 in going from sea level to 10,000 feet and by about 15% in going from 0° to 50° geomagnetic latitude. Reported natural background radiation levels for the United States range from about 90 to 200 millirems per year. In some parts of the world, such as the Kerala regions of India and the States of Minas Gerias and Espirito Santo of Brazil, much higher levels prevail.(2) Radiation from thorium-bearing monazite sands in these areas makes the external environmental absorbed dose 10 to 30 times the world average. Man has reached his present state of development in the presence of background radiation; it is apparently an amount with which he can live compatibly.

Today, background radiation is only one of many sources to which the world's population is exposed. Radiation-generating machines and radioactive materials present in many phases of the environment constitute the principal manmade sources.

TABLE 1.--Representative Distribution of Natural Background Radiation

Source	Dose (mrem/yr)	
	Gonad	Bone Marrow
External		
Cosmic Rays	50	50
Terrestrial*	50	50
Internal		
Potassium	20	15
Radium	1.3	1.6
Lead	0.3	0.4
Carbon	0.7	1.6
Radon	3.0	3.0
Total	125	122

*This is due to the presence in the earth's crust of natural radioactive elements, principally those associated with the uranium, thorium, and actinium decay series and with potassium.

II. X RAYS

X-ray machines are finding widespread use in industry, medicine, commerce, and research. All such uses are potential sources of exposure.

A. Medical and Dental Use

Currently, over 200,000 medical and dental x-ray units are used in the United States for diagnosis and therapy. Some 98,000 of these units are used by dentists, with 100,000 to 130,000 employed by medical practitioners, radiologists, hospitals, and clinics.(3)

Surveys indicate that a substantial number of medical-technical personnel are occupationally exposed in the operation of these machines. In addition, a considerable portion of the general population is exposed during diagnostic and therapeutic procedures. On the average, over half the people in the

United States are exposed to x rays for medical or dental purposes each year. In 1964, the number of persons x rayed(4) was approximately 108 million--12 million of whom had more than one category of x-ray procedure which results in the following distribution:

66 million for radiographic procedures
46 million for dental diagnosis
8 million for fluoroscopy
600 thousand for x-ray therapy

B. Industrial Use

Industrial x-ray devices include primarily: (1) radiographic and fluoroscopic units used to determine defects in castings, fabricated structures and welds, and (2) fluoroscopic units used to find foreign material in such items as food products. At present, there are slightly more than 10,000 industrial radiographic installations in the United States.(3)

C. Commercial Use

A major use of x-ray machines has been in shoe-fitting. In 1950, there were almost 10,000 such units in operation in the United States.(5) Health authorities considered such exposures unnecessary, and the application of x-ray fluoroscopes in shoe-fitting has been banned or severely restricted in most States. The number remaining in operation today is small.

D. Research Use

High-voltage x-ray machines and particle accelerators are familiar features of research laboratories in universities and similar institutions. In 1941, there were only 16 cyclotron laboratories in the United States. Today, well over 600 accelerator installations (which include cyclotrons, synchrotrons, van de Graaff generators, and betatrons) are in operation.(3,6) Other x-ray equipment used in research includes diffraction units. Over 4,000 of these units are currently in use.

An emerging source of manmade, machine-produced radiation is the neutron generator. In 1966, there were over 200 of these with about 50 additional units being sold annually. Cathode-ray tubes, high-voltage electronic rectifiers, transmitting valves, and television and image tubes can also be significant sources of x-ray exposure if voltages are high and protection is inadequate.

III. RADIONUCLIDES

A. Naturally Occurring

The naturally occurring radionuclide most widely used in medicine and industry is ^{226}Ra. In considering the health aspects of naturally occurring radionuclides such as ^{226}Ra, it should be noted that this radionuclide is not covered by AEC regulations and, in some states, can essentially be purchased on the open market. Recently some states have enacted legislation on registration and licensing of naturally occurring radionuclides.

The history of the application of radium and its daughter product is replete with instances of injury and death. This is particularly true in the radium dial painting industry and in mining operations. Even today, radium continues to be a problem, especially in its medical applications. A recent survey in Georgia(7) revealed that of 210 hospitals contacted, 24 owned or leased radium and 40 more allowed its use in their facilities. For the 24 hospitals, the amount of radium on hand ranged from 50 to 440 milligrams (millicuries) and the numbers of treatments ranged from 1 to 100 per year. On-site surveys showed that eight of the 24 hospitals had one or more leaking sources. Only five routinely performed leak tests.

The national inventory of radium has been estimated at 2,000 grams. About 700 grams can be accounted for as sealed sources. Of the remaining 1300 grams, perhaps 65 to 70 percent has gone into various luminous compounds for use on wrist watches, aircraft, military instruments, etc. The 700 grams that are identifiable are used in approximately 4,500 facilities: approximately

1,000 hospitals and clinics, 1,700 private practitioners' offices, and about 1,800 industrial research and educational institutions.[8]

B. Artificially Produced

Radionuclides can be produced on a practical scale by neutron irradiation in reactors, by recovery from fission wastes, or by bombardment of target materials by charged particles in accelerators.

The United States has tremendous reactor production capacity. Large amounts of cesium-137, strontium-90, promethium-147, and other fission products are present in fission wastes at the United States Atomic Energy Commission's fissionable materials production sites. The Commission has announced that megacurie amounts of a variety of radioisotopes are available for purchase.[9] (See Tables 2 and 3.)[10]

Over 11,000 universities, hospitals, and research laboratories in the United States are using manmade radionuclides for medical, biological, industrial, agricultural, and scientific research and for medical diagnosis and therapy.[3, 11] The Atomic Energy Commission and various state health departments have issued over 3,700 licenses to the medical profession.[3,11] These licenses authorize medical institutions and private physicians to use radionuclides for the diagnosis and treatment of illness. Over a million people in the United States receive this treatment each year.

Harmful exposure from such radionuclides is possible in their preparation, handling and application, and transportation. Exposures, internal and external, might also arise through contamination of the environment by wastes originating from the use of these materials.

IV. NUCLEAR REACTOR OPERATIONS

Sources of radiation exposure associated with nuclear reactor operations include the reactor itself, its ventilation and cooling wastes, procedures associated with the removal and reprocessing of its "spent" fuel and the resulting fission product wastes, and procedures associated with the mining, milling, and fabrication of new fuels.

There are nearly thirty power reactors, with approximately ten million kilowatts capacity, now operable or under construction in the United States. An additional 45 nuclear power plants with 33 million kilowatts are planned to be operational by 1976.[12]

The most extensive military application of reactors is for propulsion of Navy ships. At the end of 1967, there were 79 nuclear-powered ships in the active fleet: 75 submarines and four surface vessels (the aircraft carrier Enterprise, the cruiser Long Beach, and the guided missile frigates Bainbridge and Truxton). Under construction were 29 additional submarines and negotiations were underway for construction of another nuclear aircraft carrier. Some vessels are powered by more than one reactor. (For example, the aircraft carrier Enterprise has eight nuclear reactors.)[13, 14]

The Navy has also launched a series of TRANSIT navigation satellites powered by plutonium-238 thermoelectric generators.[15] It has also placed a series of nuclear-powered signal-producing devices on the ocean floor in various parts of the world.

Much work has also gone into the theory of atomic-powered flight and space systems development employing isotopic heat and power applications. In addition, there will be the need for more land-based research facilities and reactor-powered research propulsion units.

Many workers are currently engaged in uranium mining and milling operations in this country, primarily in the New Mexico and Colorado Plateau regions. The number of workers involved in the fabrication of new fuels and reprocessing of "spent" fuels is currently on the increase. The predicted activity in terms of curies of fission product wastes from such operations is extensive. In addition to this occupational exposure, the general population is potentially subject to low-level internal and external radiation

TABLE 2.--Total Distribution (Ci/yr) of Radioactive Material

	Estimated Volume		Potential Volume	
	1962	1970	1962	1970
Tritium	13,025	16,025	213,000	217,000
Krypton	52	8,501	52	8,501
Promethium	50	--	50	200
Polonium	1,750	2,500	1,750	2,500
Others	--	--	--	--
Total	14,877	27,026	214,852	228,201

TABLE 3.--Product Use (Ci/yr) of Radioactive Material

Use	Estimated Volume		Potential Volume	
	1962	1970	1962	1970
Direct Purchase Products				
Air ionizers	2	2	125,000	125,000
Portable air ionizers	23	23	75,000	75,000
Anti-static devices	1,750	2,500	1,750	2,500
Auto altimeters	50	--	50	200
Educational kits	<0.2	<0.3	<0.2	<0.3
Total	1,825	2,525	201,800	202,700
Continuous Exposure Products				
Aircraft signs	12,000	16,000	12,000	16,000
Railroad signals	51	8,500	51	8,500
Watershed tracers	1,000	--	1,000	1,000
Discriminator tubes	1	1	1	1
Iron ore tracers	--	--	--	--
Petroleum and pipeline interface tracers	--	--	--	--
Total	13,052	24,501	13,052	25,501

exposure associated with the possible escape and release of reactor wastes to the environment.

V. WEAPON TESTING

The worldwide total of nuclear detonations through 1962 is probably over 300. More important than the number of detonations is their energy yield, an indication of the quantity of fission products produced. Information released at the 1959 Congressional "Fallout Hearings" showed that 90 to 92 megaton fission yield equivalent had been released to that date. Table 4 (16) summarizes the fission and total yields of atmospheric tests conducted by all nations through 1962. Some radioactive materials from these detonations remain for a time in the upper atmosphere. However, measurable amounts of fallout are widely distributed over the United States, causing a temporary average increase in radioactivity throughout the country.

VI. POPULATION DOSE

In expressing radiation exposure, one should specify the part of the body being considered. Because of genetic effects, many people consider the dose to the gonads or reproductive organs of prime importance. Typical exposures from natural background and manmade sources are summarized in Tables 1 and 5. (1, 17)

VII. CONTROL PROCEDURES

With increasing knowledge and experience in radiological health, measures for

TABLE 4.--Approximate Yields (in Megatons) of Atmospheric Nuclear Tests Conducted by All Nations

Inclusive years	Fission Yield		Total Yield	
	Air	Surface	Air	Surface
1945 to 1951 . . .	0.19	0.52	0.19	0.57
1952 to 1954. . . .	1	37	1	59
1955 to 1956. . . .	5.6	7.5	11	17
1957 to 1958	31	9	57	28
Subtotal	37.8	54	69.2	104.6
1959 to 1960. . . .	*	*	*	*
1961	25 †		120	
Subtotal	63	54	189	105
1962.	76 †		217	
Total	139	54	406	105

* Test moratorium.

† The small-yield tests conducted in Nevada do not contribute significantly to the worldwide distribution of strontium-90 to which this summary is related.

minimizing radiation exposures have been developed.

A. X-ray Control

Control procedures for protecting the operators of medical, dental, and industrial x-ray machines consist of limiting the time of exposure, maintaining an adequate distance between the x-ray beam and the operator, and using adequate shielding. Generally, a combination of these three safety measures can restrict the dose to acceptable levels.

In protecting the patient, two important factors are: limitation of the size of the beam through proper coning or collimation, and filtration of the beam to remove soft x rays which would otherwise be absorbed by the body. Experience has shown that the use of proper filtration can result in a two- to fivefold reduction in the dose to the reproductive organs of the patient; through proper coning, the genetic dose can be reduced by a factor of 200 to 500.(18)

B. Radioactive Materials

For radioactive materials, containment and isolation or dilution and dispersion are the main control procedures. Containment and isolation is the method of choice for low-volume high-level wastes; dilution and dispersion is used for large-volume low-level wastes. Intermediate-level wastes are generally handled by a combination of the two approaches; the radioactive material content is concentrated and confined with the decontaminated residue released to the environment. The chemical nature of certain radionuclides makes this combined approach difficult to apply. Examples of intermediate-level wastes are hydrogen-3 and krypton-85—two of the contaminants produced in nuclear reactor operations and fuel reprocessing plants.

VIII. COMMENTARY

For the United States, estimates indicate that medical and dental x rays contribute about one-third of the current genetic dose to man; natural background accounts for approximately 60 percent; and less than 10 percent arises from nuclear reactor operations, weapons testing fallout, and other manmade sources. When planning control procedures to minimize such exposures, it is important to consider the relationship between the dose and the resulting biological effects.

Such considerations are also uppermost in the minds of those responsible for the establishment of Radiation Protection Guides.(17) Most toxic materials, for example, have a threshold dose which, it is felt, must be exceeded before effects appear. When this is the case, control procedures are straightforward and the primary objective is to keep the dose below the threshold. With ionizing radiation, however, it is believed that even the smallest dose may be capable of producing harmful genetic effects. The same relationship may hold for somatic effects.

Since radiation damage may have no threshold, the philosophy of radiation control generally reflects a weighing of the benefits of the particular radiation application against the risks of the associated exposure. That is, the dose must always be kept below the level at which the harmful effects would be considered to outweigh the benefits.

Based on these considerations, experts (17) have made recommendations for the safe conduct of radiation operations. Guide levels have also been established for the general population. These provide criteria for minimizing genetic and somatic damage. For health personnel, the challenge is to be familiar with exposure sources, to understand the effects of exposure upon man, and to establish effective control programs which will keep occupational and environmental exposures at acceptable levels.

The increasing magnitude of radiation-producing sources is shown in Figure 1. Simultaneous with this increase, the recommended maximum permissible levels for radiation exposure, now called Radiation Protection Guides,(17) have decreased sharply. The magnitude and sequence of this decrease is seen in Figure 2.

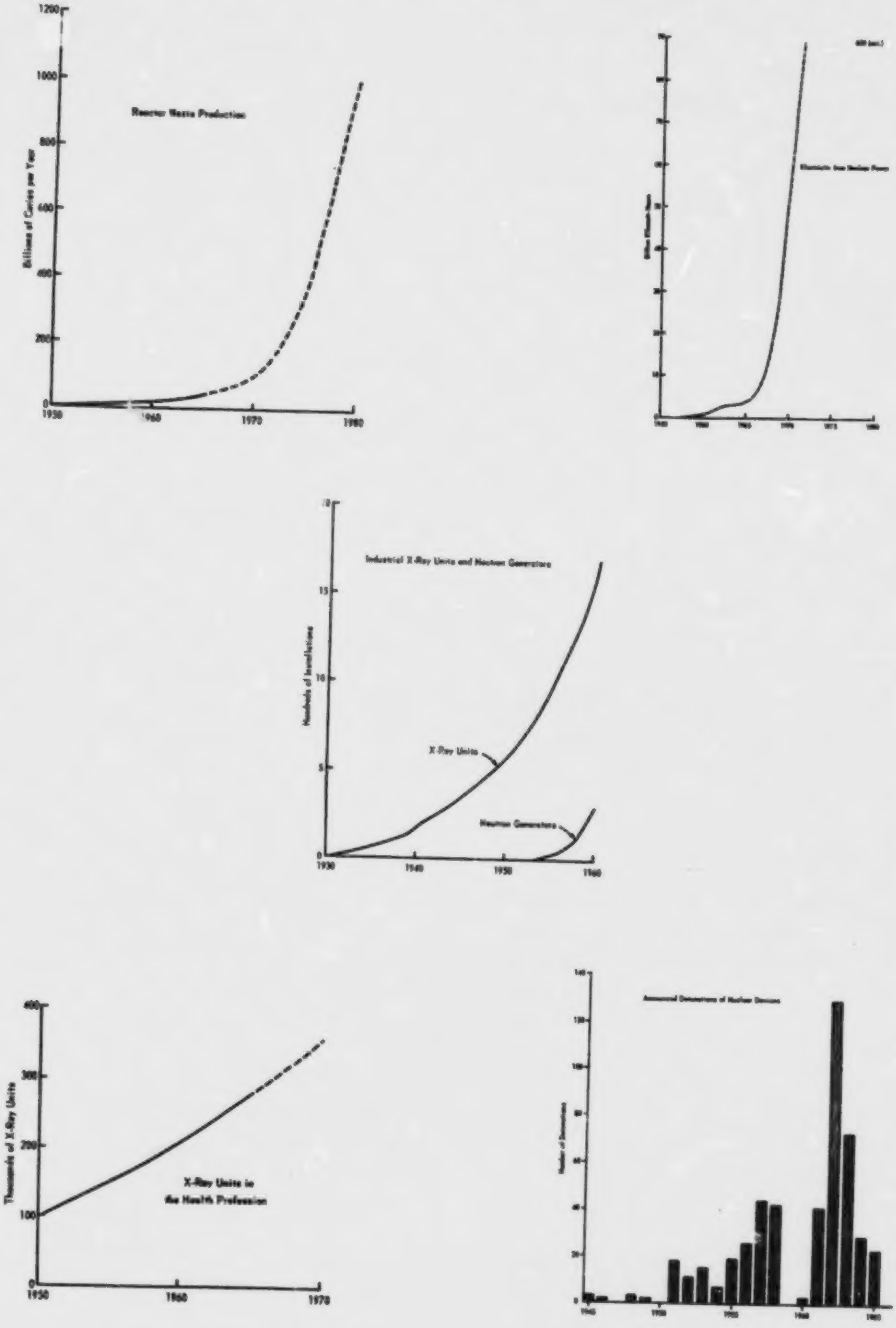

Figure 1.--Increased Use of Radiation

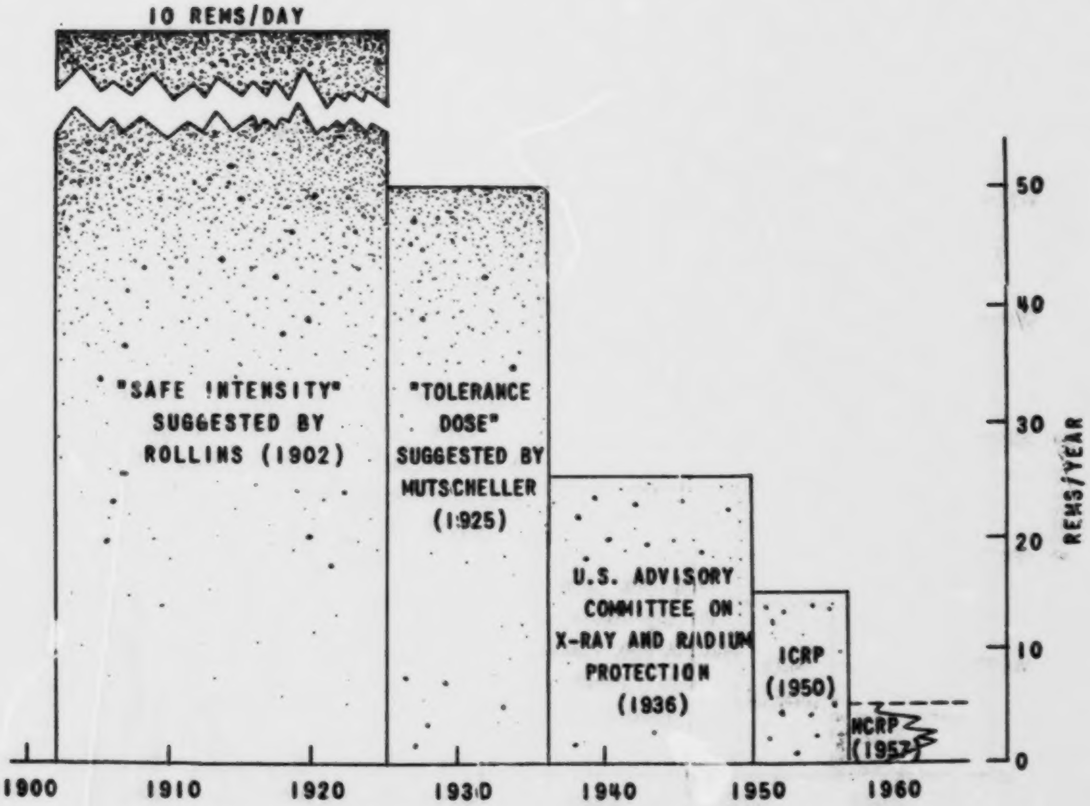

Figure 2.--Decrease in Maximum Permissible Levels (Occupational Whole-Body Exposure)

TABLE 5.--Estimated Annual Genetic Doses (rem/yr) from Manmade Radiation

Medicine and dentistry:		
Diagnostic	0.040 - 0.240*	
Therapeutic	0.012	
Internal (radionuclides)	0.001	
Total		0.053 - 0.253
Occupational		0.020
Environs		0.005
Other		0.002
Total		0.080 - 0.280†

*The U.S. Public Health Service x-ray Exposure Study estimated 0.055 rem/yr from medical and dental x-rays.(4)

† In addition, it is estimated that fallout will contribute from 0.002 to 0.015 rem/yr to the genetically significant per capita dose, depending upon the amount of atmospheric nuclear weapons testing.(18)

The currently recommended Radiation Protection Guide for the genetic dose to general population groups is 5 rems in 30 years, exclusive of natural background and the purposeful exposure of patients. Table 5 shows that exposures associated with medical procedures make a significant contribution to the current dose.

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This material was prepared by Messrs. Michael S. Terpilak and George J. Gruber of TMDP, National Center for Radiological Health.

Atomic Structure

I. INTRODUCTION

To understand the various processes of radioactive decay, it is necessary to understand the structure of the atom.

This review presents the fundamental concepts of stable atoms, the symbols, units, and terminology commonly used in nuclear physics and radiological health and the concepts of ions, isotopes, and nuclear binding energy.

II. STRUCTURE OF THE ATOM

A. General

The atom is the simplest unit into which an element can be divided and still retain the properties of the original element. Atoms of all elements are made of three primary subatomic components: electrons, protons, and neutrons. These three primary components are so arranged that the atom may be thought of as consisting of two main parts, the nucleus and the electron cloud. A graphical representation of several atoms is shown in Figure 1.

1. THE NUCLEUS

The nucleus is the central portion of the atom and contains two of the three components: the protons and neutrons. They make up practically all of the mass of the atom. Protons and neutrons are often referred to as nucleons. Thus, we consider the nucleus to consist of various combinations of protons and neutrons. It is easier to understand the following discussion if these combinations are thought of as being held together by some force sufficiently great to overcome the coulomb force of repulsion that exists between the positively charged protons. Table 1 lists the subatomic particles as to whether they are fundamental components, generated particles, or derived particles.

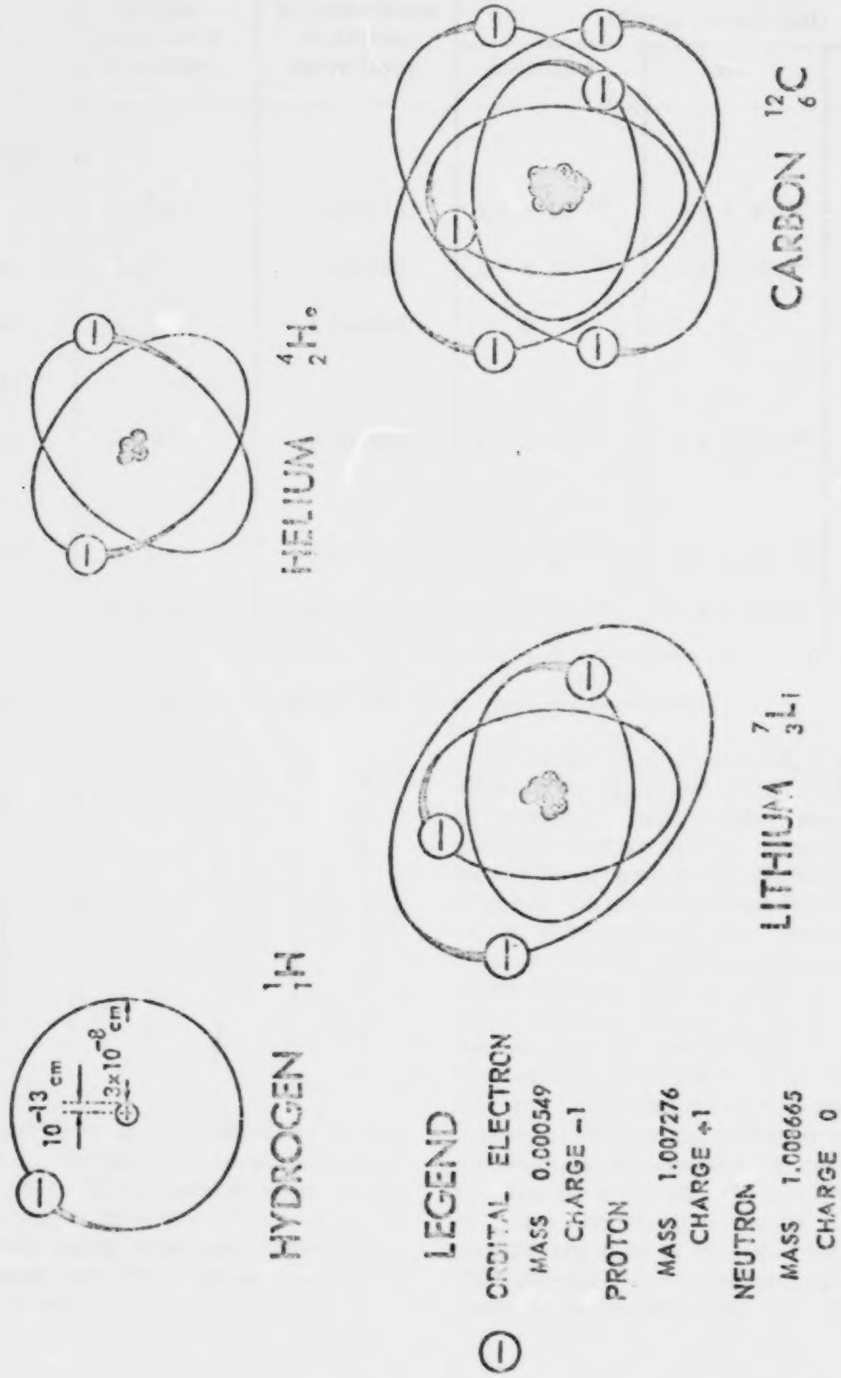
2. THE ELECTRON CLOUD

The electron cloud surrounds the nuclear portion of the atom and contains the electrons which are in motion about the nucleus. Since the atom as a whole is electrically neutral, the number of electrons in the electron cloud is equal to the number of positive charges (protons) in the nucleus.

The results of various studies[1] of the electron arrangements in atoms indicate that electrons in an atom are grouped into shells each having a definite energy and a definite maximum number of electrons. It is customary to visualize electrons of the atom as moving about the nucleus in orbits much as the planets revolve in elliptical paths about the sun. Although this mental image is not entirely accurate, it provides a useful model for understanding the atom. These well-defined orbits (or shells) are often referred to as energy (quantum) levels since a definite minimum amount of energy is required to remove an electron from a particular shell. Each shell is denoted by a number in order of decreasing binding energy or, more commonly, by a letter

---

[1] Our knowledge of the electric configurations of atoms has come chiefly from studies of atomic spectra and variation in chemical and physical properties with atomic number.

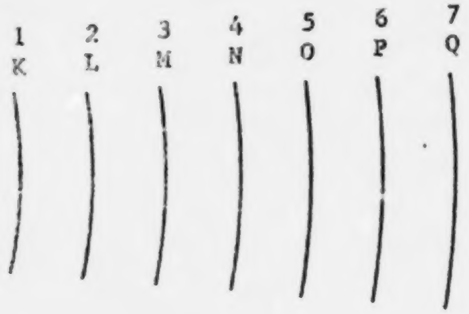

HYDROGEN $^{1}_{1}H$
10^{-13} cm
3×10^{-8} cm
HELIUM $^{4}_{2}He$
LITHIUM $^{7}_{3}Li$
CARBON $^{12}_{6}C$
LEGEND
ORBITAL ELECTRON
MASS 0.000549
CHARGE –1
PROTON
MASS 1.007276
CHARGE +1
NEUTRON
MASS 1.008665
CHARGE 0

Atomic Structure

Table 1. Atomic Components

Unit	Symbol (Common & Alternate)	Relative Mass in Atomic Mass Units	Charge (Electrical)		
			coulombs	esu	relative
Fundamental					
Proton	p, ^1_1H	1.007276	1.6×10^{-19}	4.8×10^{-10}	+
Electron	e, β^-	0.000549	1.6×10^{-19}	4.8×10^{-10}	-
Neutron	n, ^1_0n	1.008665	0	0	0
Generated					
Positron	e^+, β^+	0.000549	1.6×10^{-19}	4.8×10^{-10}	+
Derived					
Deuteron	d, ^2_1H	2.013551	1.6×10^{-19}	4.8×10^{-10}	+
Alpha	a, ^4_2He	4.001502	3.2×10^{-19}	9.6×10^{-10}	2+

designation from K to Q, as shown below.



The first shell is designated as K, the second as L, the third M, and so on through the alphabet to Q, or seventh shell, which is the outermost shell ever found in any of the presently known elements. Table 2 lists the elements and the various number of electrons in each shell.

B. Ions and Ionization

All atoms in their natural, lowest energy state have the same number of electrons as protons. Consequently, they carry no residual electric charge. When atoms combine to form compounds, the resulting molecule has the same total number of electrons as it does protons; and the molecule is also electrically neutral. Since the electron is the lightest part of the atom, and since each electron is not bound as tightly to the nucleus as the protons and neutrons are bound to each other, it is more mobile and can be removed from the atom or molecule without expending much energy. As soon as an electron is removed from an atom or molecule, the resulting component has an electric charge because the protons are then in excess of the electrons. The residual atom, remaining after the removal of an electron, and the electron

Table 2. The Atomic Structures

Period	Atom	Atomic No.	K Shell 1	L Shell 2	M Shell 3	N Shell 4	O Shell 5
1	H	1	1				
	He	2	2				
2	Li	3	2	1			
	Be	4	2	2			
	B	5	2	3			
	C	6	2	4			
	N	7	2	5			
	O	8	2	6			
	F	9	2	7			
3	Ne	10	2	8			
	Na	11	2	8	1		
	Mg	12	2	8	2		
	Al	13	2	8	3		
	Si	14	2	8	4		
	P	15	2	8	5		
	S	16	2	8	6		
	Cl	17	2	8	7		
4	A	18	2	8	8		
	K	19	2	8	8	1	
	Ca	20	2	8	8	2	
	Sc	21	2	8	9	2	
	Ti	22	2	8	10	2	
	V	23	2	8	11	2	
	Cr	24	2	8	13	1	
	Mn	25	2	8	13	2	
	Fe	26	2	8	14	2	
	Co	27	2	8	15	2	
	Ni	28	2	8	16	2	
	Cu	29	2	8	18	1	
	Zn	30	2	8	18	2	
	Ga	31	2	8	18	3	
	Ge	32	2	8	18	4	
	As	33	2	8	18	5	
	Se	34	2	8	18	6	
	Br	35	2	8	18	7	
5	Kr	36	2	8	18	8	
	Rb	37	2	8	18	8	1
	Sr	38	2	8	18	8	2
	Y	39	2	8	18	9	2
	Zr	40	2	8	18	10	2
	Nb	41	2	8	18	12	1
	Mo	42	2	8	18	13	1
	Tc	43	2	8	18	14	1
	Ru	44	2	8	18	15	1
	Rh	45	2	8	18	16	1
	Pd	46	2	8	18	18	0
	Ag	47	2	8	18	18	1
	Cd	48	2	8	18	18	2
	In	49	2	8	18	18	3
	Sn	50	2	8	18	18	4
	Sb	51	2	8	18	18	5
	Te	52	2	8	18	18	6
	I	53	2	8	18	18	7

Period	Atom	Atomic No.	K Shell 1	L Shell 2	M Shell 3	N Shell 4	O Shell 5	P Shell 6	Q Shell 7
6	Xe	54	2	8	18	18	8		
	Cs	55	2	8	18	18	8	1	
	Ba	56	2	8	18	18	8	2	
	La	57	2	8	18	18	9	2	
Rare Earths	Ce	58	2	8	18	19	9	2	
	Pr	59	2	8	18	20	9	2	
	Nd	60	2	8	18	22	8	2	
	Pm	61	2	8	18	23	8	2	
	Sm	62	2	8	18	24	8	2	
	Eu	63	2	8	18	25	8	2	
	Gd	64	2	8	18	25	9	2	
	Tb	65	2	8	18	26	9	2	
	Dy	66	2	8	18	28	8	2	
	Ho	67	2	8	18	29	8	2	
	Er	68	2	8	18	30	8	2	
	Tm	69	2	8	18	31	8	2	
	Yb	70	2	8	18	32	8	2	
	Lu	71	2	8	18	32	9	2	
	Hf	72	2	8	18	32	10	2	
	Ta	73	2	8	18	32	11	2	
	W	74	2	8	18	32	12	2	
	Re	75	2	8	18	32	13	2	
	Os	76	2	8	18	32	14	2	
	Ir	77	2	8	18	32	15	2	
	Pt	78	2	8	18	32	17	1	
	Au	79	2	8	18	32	18	1	
	Hg	80	2	8	18	32	18	2	
	Tl	81	2	8	18	32	18	3	
	Pb	82	2	8	18	32	18	4	
	Bi	83	2	8	18	32	18	5	
	Po	84	2	8	18	32	18	6	
	At	85	2	8	18	32	18	7	
7	Rn	86	2	8	18	32	18	8	
	Fr	87	2	8	18	32	18	8	1
	Ra	88	2	8	18	32	18	8	2
	Ac	89	2	8	18	32	18	9	2
Rare Earths	Th	90	2	8	18	32	19	9	2
	Pa	91	2	8	18	32	20	9	2
	U	92	2	8	18	32	21	9	2
	Np	93	2	8	18	32	22	9	2
	Pu	94	2	8	18	32	23	9	2
	Am	95	2	8	18	32	25	8	2
	Cm	96	2	8	18	32	25	9	2
	Bk	97	2	8	18	32	26	8	2
	Cf	98	2	8	18	32	27	9	2
	Es	99	2	8	18	32	28	9	2
	Fm	100	2	8	18	32	29	9	2
	Md	101	2	8	18	32	30	9	2
	No	102	2	8	18	32	31	9	2
	Lw	103	2	8	18	32	32	9	2

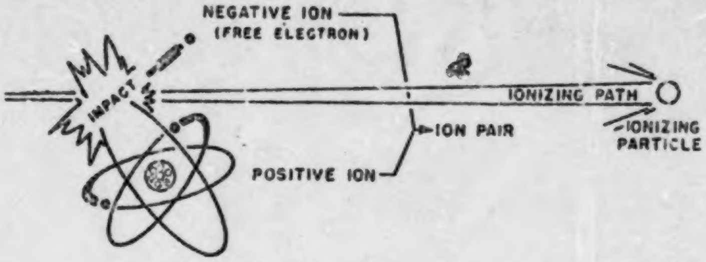


Figure 2. Ionization

itself are called ions. These are shown in Figure 2.

Ions may be charged positively or negatively and may exist in crystals, liquids, or in gases. Positive ions are produced by removing electrons from neutral atoms and molecules, whereas negative ions are created when electrons attach themselves to neutral atoms or molecules. Negative ions are also free electrons and electrons that have been removed from atoms and molecules. The magnitude of the electrical charge on the ion, in terms of electron units, is equal to the number of electrons removed from or added to a neutral atom or molecule. The magnitude of electrical charge on an ion may be calculated in terms of coulombs or electrostatic units by multiplying the number of electrons exchanged (gained or lost) by the charge on each electron in coulombs or electrostatic units. This value is given in the table of atomic components.

As shown in Table 1, the relative charge on an ion in terms of electron units is called the valence of the ion. Recently it has become common practice to consider a free electron as an ion. Ions are, therefore, defined as free electrons or atoms or groups of atoms carrying an electric charge.

Ionization is the process of producing ions. Anything which is able to bring about the removal of electrons from neutral atoms or molecules is capable of causing ionization or an ionizing event. Consequently, the ionizing event is spoken of as producing an ion pair which consists of the removed electron and the residual positive ion.

III. ATOMIC NOMENCLATURE

Before proceeding, it will greatly simplify the discussion of the atom to introduce a consistent set of definitions and symbols.

A general expression for representing a particular element is ${}^{A}_{Z}X$.

A. Chemical Symbols

In the general expression above, the X represents the chemical symbol of the element and is used for brevity and convenience. In referring to a specific element, the chemical symbol usually consists of the initial letter[2] (capitalized) in the name of the element or the initial letter followed by an appropriate second letter. For example, carbon is represented by C, chlorine by Cl, calcium by Ca, Oxygen by O, and hydrogen by H.

B. Atomic Number (Z)

The Z refers to the number of protons present in the atomic nucleus. This number is always the same as the number of positive charges and is called the atomic number of the element. Since atoms are electrically neutral, the number of electrons in the electron cloud is the same as the number of protons within the nucleus. Each element has an atomic number which is characteristic of the element and is synonymous with the chemical symbol. There are currently 103 elements, 103 symbols, and 103 atomic numbers. Consequently, an element may be designated in any one of the three ways by name, by number, or by letter symbol.

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[2] When this system was adopted (1779-1898), the Latin names for several metals were in common use. This is reflected in such symbols as Fe (from the Latin ferrum) for iron, Cu (cuprum) for copper, Au (aurum) for gold, Ag (argentum) for silver, Sn (stannum) for tin, and Sb (stibium) for antimony.

C. Mass Number (A)

The A in the general expression ($^{A}_{Z}X$) represents the total number of particles (protons and neutrons) in the nucleus and is referred to as the mass number. The mass number is approximately equal to the atomic weight of an element.

D. Neutron Number (N)

The number of neutrons in the nucleus is called the neutron number (N) and is equal to the mass number minus the atomic number (A-Z).

1. ISOTOPES

When the atoms of an element have the same number of protons but a different number of neutrons, they are said to be isotopes of the element. Such atoms are, in general, indistinguishable chemically. The chemical properties of the isotopes of an element are the same because the chemical properties depend on the number and arrangement of (orbital) electrons surrounding the nucleus which, in turn, is determined by the number of protons in the nucleus.

For example, there are three naturally-occurring isotopes of oxygen, namely, $^{16}_{8}O$, $^{17}_{8}O$, and $^{18}_{8}O$. The isotope which has a mass number of 16 occurs most abundantly. Another example is hydrogen which has three isotopes, $^{1}_{1}H$, $^{2}_{1}H$, and $^{3}_{1}H$. This element is so significant that its three isotopes are sometimes called by distinct names. The isotope of mass number 1 is called hydrogen, that of 2 is deuterium, and that of 3 is tritium.

IV. SIZE OF ATOMIC AND SUBATOMIC PARTICLES

A. Radius of the Nucleus

The radius of the nucleus of various nuclides, determined by different experimental methods, are generally in good agreement with each other. Except for the elements of lowest mass number, the size of the nucleus can be expressed by the following empirical equation:

$$r = r_o A^{1/3}, \text{ where}$$

r = the radius of the nucleus of an isotope

r_o = a constant of about 1.37×10^{-13} cm

A = the mass number.

Figure 3 shows the extent to which the equation holds for specific elements.

1. NUCLEAR DENSITY

Since the radius is proportional to the cube root of the mass number and the volume of a sphere (volume = $4/3\,\pi\, r^3$) is proportional to the cube of the radius, the volume of the nucleus is, consequently, directly proportional to the mass number and, hence, to its actual mass. Thus, since all atomic nuclei are composed of the same constituents, namely, neutrons and protons, they have essentially the same density. This density can easily be determined since the protons (and neutrons) have a mass of about 1.67×10^{-24} gm. The radius (A = 1) from the equation $r = r_o A^{1/3}$ is about 1.37×10^{-13} cm. The density is, thus, approximately 10^5 tons/mm^3.

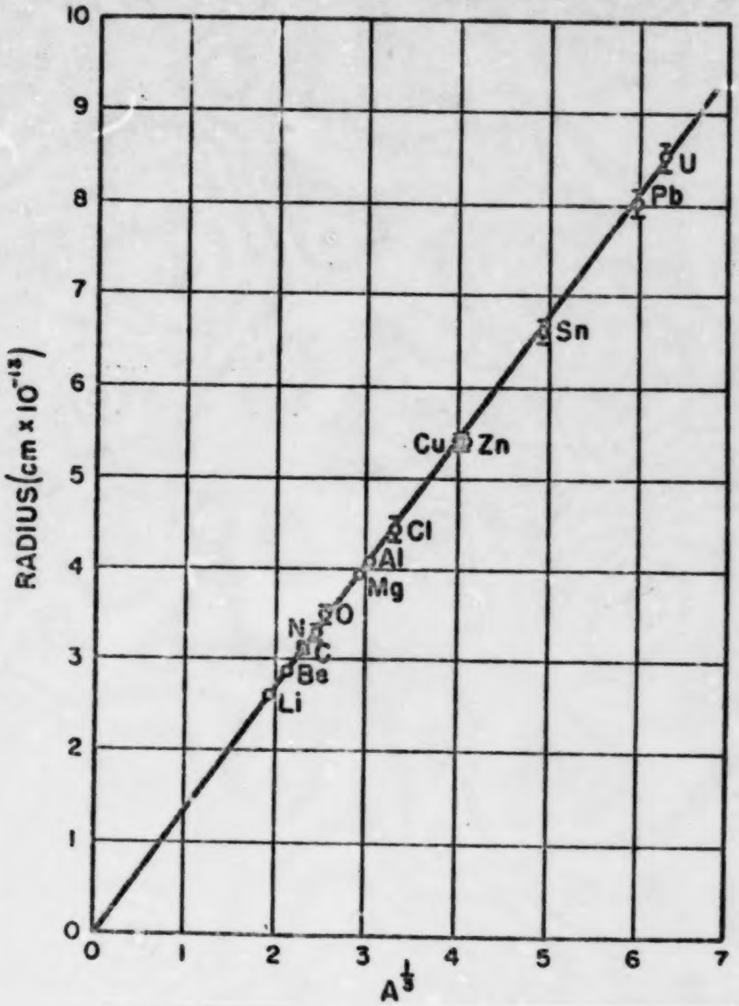

Figure 3. Radius of the Atom and its Nucleus

B. Radius of the Atom

The radius of the entire atom is much larger than the radius of the nucleus, as shown in Table 3.

Table 3. Radius of the Atom and its Nucleus

Element	Radius of Atom	Radius of Nucleus
Carbon	$.77 \times 10^{-8}$ cm	3.8×10^{-13} cm
Aluminum	1.45×10^{-8} cm	4.6×10^{-13} cm
Argon	1.5×10^{-8} cm	4.1×10^{-13} cm
Tin	1.4×10^{-8} cm	7.4×10^{-13} cm
Lead	1.6×10^{-8} cm	7.8×10^{-13} cm

For example, the radius of the argon atom is about 1.5×10^{-8} cm, whereas the radius of the nucleus is only 4.1×10^{-13} cm. Thus, the radius of the argon atom is about 40,000 times larger than the radius of its nucleus. This difference between the size of the atom and its nucleus indicates that a great deal of the atom is empty space. Considering the size of the atom at about 10^{-8} and the nucleus at 10^{-13}, calculations show that only about one-trillionth (10^{-12}) of the volume of an atom is occupied by material particles.

V. UNITS OF NUCLEAR MASS AND ENERGY

A. Atomic Mass Unit (amu)

To appreciate the meaning of the atomic mass unit, consider the relative mass of the nuclear particles as shown in Table 4.

Since the mass of an individual nuclear particle is very small and, when expressed in grams, involves the use of unwieldly negative exponents, the system of atomic mass units (amu) was developed using the most plentiful isotope of oxygen ($^{16}_{8}O$) as a reference atom. The present standard utilized carbon-12 as the reference atom. The arbitrary value (weight) of 12 units has been assigned to carbon-12 ($^{12}_{6}C$). The mass of all other atoms is based on a unit which is 1/12 the weight of the carbon-12 atom. The mass of the lightest isotope of hydrogen is approximately 1 (1.007825 amu).

The weight in grams of an isotope numerically equal to its atomic mass is called a gram-atomic weight. Since gram-atomic masses are relative magnitudes, proportional to the actual masses of the individual atoms, it follows that one gram-atomic weight of any substance contains a definite number of atoms. The number of atoms in one gram-atomic mass is known as Avogadro's number (N_0) and is equal to 6.023×10^{23} atoms/gram-atomic weight.

• The mass of any atom in grams can thus be found by dividing the gram-atomic mass of the isotope by Avogadro's number. For example, the mass of an atom of carbon-12 is its gram-atomic mass (12 gm.) divided by Avogadro's number (N_0).

$$\text{Mass of } ^{12}\text{C} = \frac{12 \text{ gm}}{6.023 \times 10^{23}}$$

$$= 1.99 \times 10^{-23} \text{gm}/^{12}\text{C atom}$$

Since ^{12}C is equal to 12 atomic mass units (amu), the mass of 1 amu would be one-twelfth of the mass of a carbon-12 atom.

$$1 \text{ amu} = \frac{1.99 \times 10^{-23} \text{ gm}/^{12}\text{C}}{12 \text{ amu}/^{12}\text{C}}$$

$$= 1.66 \times 10^{-24} \text{ gm}$$

Table 4. Relative Mass of Nuclear Particles

Particle	Weight in Grams	Number in One Gram	Symbol	Charge
Neutron	1.67482×10^{-24}	5.9724×10^{23}	n	0
Proton	1.67252×10^{-24}	5.9790×10^{23}	p	+1
Electron	9.1091×10^{-28}	1.0978×10^{27}	e	-1

B. The Erg

To facilitate an understanding of the enormous energy contained in a small mass, consider the energy produced if one amu (1.66×10^{-24} gm) is converted into energy. This conversion can be expressed by Einstein's famous equation relating mass and energy.

$$E = mc^2$$

where: m = the mass in grams

c = the velocity of light

$$E = (1.66 \times 10^{-24} \text{gm})(3 \times 10^{10} \text{cm/sec})^2$$

$$= 1.494 \times 10^{-3} \text{gm-cm}^2/\text{sec}^2$$

The unit $\text{gm-cm}^2/\text{sec}^2$ is frequently encountered in physics and radiological health work. For brevity, it is commonly referred to as an erg, thus:

$$1.494 \times 10^{-3} \text{gm-cm}^2/\text{sec}^2 = 1.49 \times 10^{-3} \text{ ergs}$$

C. The Electron Volt

Another convenient unit of energy is the electron volt. An electron volt is defined as the amount of energy acquired by an electron when it is accelerated in an electric field which is produced by a potential difference of one volt. Since the work done by a difference of potential, V, acting on a charge, e, is eV, then, because $e = 1.6 \times 10^{-19}$ coulomb, it is possible to calculate as follows:

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ coulomb} \times 1 \text{ volt}$$

$$= 1.6 \times 10^{-19} \text{ joule}$$

$$1 \text{ eV} = 1.6 \times 10^{-12} \text{ ergs}$$

Since the electron volt is a very small amount of energy, it is more commonly expressed in thousands of electron volts (keV) or millions of electron volts (MeV).

1 million electron volts (MeV)

= 1,000,000 electron volts

1 kilo-electron volts (keV)

= 1000 electron volts

It is now possible to express the atomic mass unit in MeV. Since 1 amu = 1.49×10^{-3} ergs, and 1 MeV = 1.60×10^{-6} ergs, 1 amu = 931 MeV.

Therefore, if one amu could be completely transformed into energy, 931 MeV would result. To gain a concept of the magnitude of the electron volt, it may be pointed out that one MeV is the energy necessary to lift a milligram weight one-millionth of a centimeter.

VI. NUCLEAR BINDING ENERGY

The atomic mass of a nuclide can be understood in terms of the masses of its constituent particles and a quantity called the nuclear binding energy. It might be thought that the mass of an atom would be equal to sum of the masses of the individual particles composing the atom. However, precise measurements of atomic masses show that the mass of an atom is always less than the sum of its constituent particles (as measured in the free state). This difference is called the mass defect and is the amount of mass which would be converted into energy and released (to hold the nucleons together) if an atom were assembled from free neutrons, protons, and electrons. Since this is also the amount of energy required to split an atom into its component particles, it is called the binding energy of the particular atom. The relationship between binding energy and mass defect is given by Einstein's equation, $E = mc^2$.

The binding energy varies from atom to atom and is usually expressed in terms of the binding energy per nucleon in a particular atom. The chart above shows a plot of the binding energy per nucleon against the mass number (A) for the most stable atoms in nature.

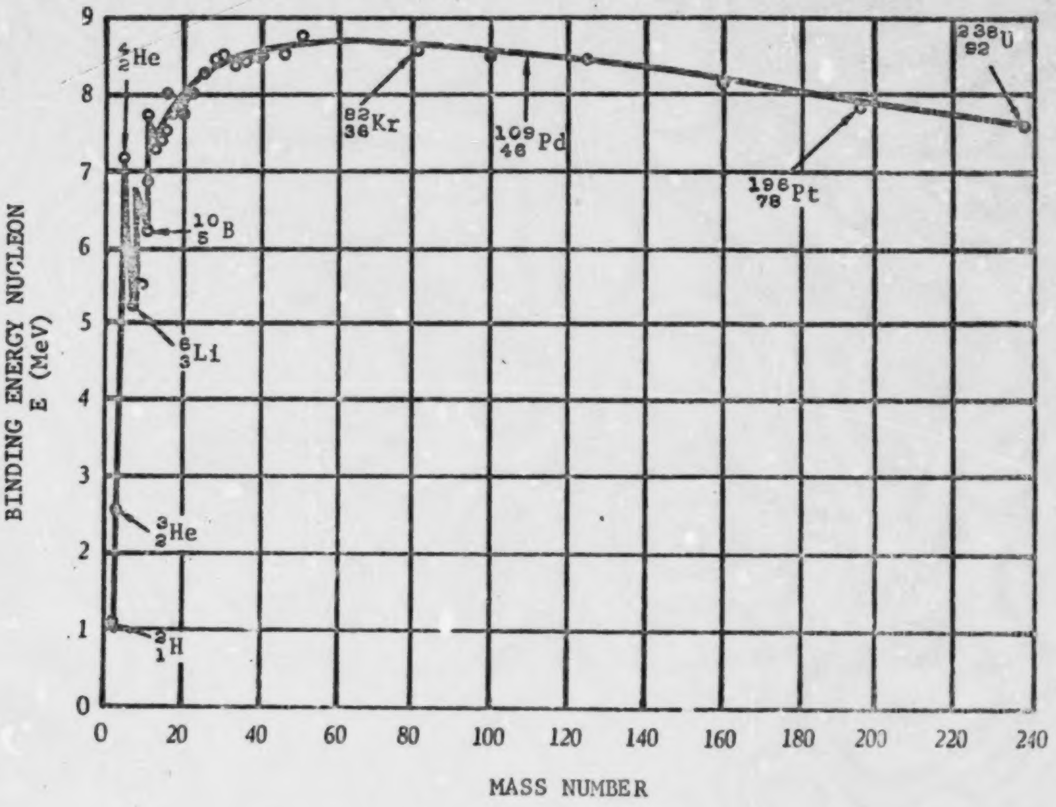

Figure 4. Binding Energy vs. Mass Number

Important features of Figure 4 are (1) a central region for which the average binding energy is nearly constant (≅8.5 MeV/nucleons); (2) regions at either end of the curve featuring a smaller binding energy per particle (which means a less stable nucleus for both small and large mass numbers); and (3) an unusually large binding energy for small mass numbers having nucleons in multiples of four.

Consider the formation of deuterium as a simple example of the meaning of binding energy. Deuterium is made up of one proton and one neutron in the nucleus, and one electron outside. The atomic mass of deuterium is 2.01410 amu. The sum of the masses of its component particles, however, is:

mass of proton	=	1.00728
mass of neutron	=	1.00866
mass of electron	=	.00055
sum		2.01649

Thus, the mass of the deuterium atom is less than the mass of its component particles by an amount of .00239 amu.

Since 1 amu is equivalent to 931 MeV, the binding energy of the deuterium atom may now be written as:

$$E = .00239 \times 931\ \text{MeV} = 2.23\ \text{MeV}$$

The binding energy of the electron is approximately 14 eV and is, therefore, negligible in comparison with 2.23 MeV. Thus, the entire binding energy is essentially that of the two nucleons in the nucleus of the deuterium atom or about 1.11 MeV each.

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Radioactivity

I. INTRODUCTION

The atom is comprised of a nucleus, consisting of neutrons and protons, and orbital electrons. The atomic number (Z) and the mass number (A) describe the quantity of these atomic components. There are 92 naturally occurring elements with atomic numbers ranging from 1 to 92. The atomic masses are approximately integral numbers that increase roughly in proportion to the atomic numbers. All elements have several isotopes, differing in mass by one or more mass units from each other. The integral nature of the increments, both in atomic number and mass number, suggests that the nucleus itself is a structure of particles (protons and neutrons) with about one atomic mass unit each. The protons carry one unit positive charge; the neutrons are neutral.

Certain structural criteria must be satisfied for a nucleus to exist in a stable state. When these criteria are not met, the nucleus will be unstable and manifest the phenomenon of radioactivity. Radioactivity refers to the processes by which a nucleus decays--or disintegrates--by one or more discrete energy steps or transitions, until a stable state is reached. The criteria which determine a nucleus's stability or instability are briefly discussed in the following section.

II. NUCLEAR STABILITY

There are two sets of forces acting on the particles within the nucleus: the relatively long-range coulomb forces of repulsion between the positive charges on the protons, and the very short-range forces between both types of particles. These latter forces are only partly understood; no attempt will be made here to discuss them. Suffice to say the combined effects of these attractive and repulsive forces are such that only certain combinations or ratios of neutrons and protons are stable.

Theoretically, if the coulomb forces were discounted, optimum stability would be achieved within a nucleus when the numbers of protons and neutrons are approximately equal. Such is the situation for the lighter elements in which the coulomb forces, relative to the short-range forces, are insignificant. These coulomb forces become increasingly significant as the atomic number increases above 20. With large increases of these repulsive forces within nuclei, intranuclear stability conditions become altered. Consequently, with increasing atomic number a neutron excess is required for a stable nuclide.

Thus, for elements in the Periodic Table with low atomic numbers, greater nuclear stability is found when the number of neutrons is about equal to the number of protons; stated in another manner, when the ratio of neutrons to protons (n:p ratio) is approximately equal to unity. As elements increase in Z number above 20, the n:p ratio required for stability gradually increases until Z = 83 (bismuth), where the n:p ratio required for stability exceeds 1.5:1. Finally, at the high atomic number part of the Periodic Table, above $^{209}_{83}$Bi, there are no completely stable nuclei. The stability conditions based on n:p ratios are not very critical, and "stability ranges" of n:p ratios exist for any given atomic number or mass number. For a given mass number, there may be several stable arrangements of protons and neutrons resulting in several stable isobars. For a given atomic number, conditions may vary still more widely, so numerous stable isotopes can occur for a particular element--as many as 10 stable isotopes for some elements.

The n:p ratio is an oversimplified explanation of the intranuclear criteria leading to nuclear stability. Additional factors involving quantum-mechanical principles and binding energy considerations are needed to fully explain nuclear stability. These are beyond the scope of this presentation.

In summary, nuclear stability is governed by the particular combination and arrangement of neutrons and protons in a given nucleus. If the combination and arrangement of neutrons and protons does not fall within a "stable range," the nucleus is unstable. This is tantamount to saying the nucleus is radioactive. An unstable nucleus attempts to achieve stability by changing its configuration or ratio of neutrons and protons by means of spontaneous disintegration, or, radioactive decay.

III. RADIOACTIVITY

For the purpose of this discussion, a distinction will be made between natural radioactivity and artificial radioactivity.

A. Natural and Artificial

Certain nuclides are unstable as they occur in nature and are therefore called "natural" radionuclides.

Others occur as a result of various man-made reactions. The vast majority of radionuclides are produced in this manner. These are called "artificial" radionuclides. The processes involved in the production of artificial radioactivity will be discussed in detail later.

B. History

Evidence of natural radioactivity was first reported by Henry Becquerel in 1896. Becquerel demonstrated that uranium ore would fog or darken a photographic plate shielded with opaque paper in much the same manner as x rays. He postulated that the uranium emitted very penetrating rays, similar to x rays. The phenomenon ultimately was called "radioactivity." In time, it was determined that there were many elements beyond the atomic number of lead ($Z = 82$) which showed similar radiating characteristics.

After a long and complicated chain of investigations, to which many outstanding physicists contributed, a better understanding of natural radioactivity was available. The understanding culminated with the experiments of Rutherford. In 1903, he clearly showed there were three kinds of radioactive emissions, namely: alpha, beta, and gamma.

C. Types of Radioactive Emissions

Alpha particles are the least penetrating of the three types of radiation. They can be absorbed or stopped by a few centimeters of air or a thin piece of paper. They have an electric charge opposite to and exactly twice that of the electron, and a mass number of 4. Thus, an alpha particle and a helium nucleus are identical in structure. With a few exceptions, only relatively heavy radioactive nuclides decay by alpha emission.

Beta particles are negatively charged particles. They have the same mass and charge as an electron and can be considered high-speed electrons. They originate in the nucleus, in contrast with ordinary electrons, which exist in the orbits around the nucleus. They travel several hundred times the distance of alpha particles in air and require a few millimeters of aluminum to stop them. Beta activity can be expected where the n:p ratio is high. The intranuclear effect of a beta emission would be changing a neutron into a proton, decreasing the n:p ratio.

Gamma rays are a type of electromagnetic radiation and move with the speed of light. The basic difference between gamma rays and x rays is their source; gamma rays originate in the nucleus, x rays in the orbital electron structure. The basic difference between gamma rays and visible light is their frequency. The Greek symbol γ is used to designate gamma radiation.

In early investigations of radioactivity, all three of the previously mentioned radiations were commonly referred to as "rays," establishing a terminology still in use despite the fact that the term "ray" is a misnomer for particulate emissions.

Other types of emissions. There are several other types of radioactive emissions usually associated with artificial radiactivity. Because of characteristics in common with alpha, beta, and gamma rays, they are described in this section.

1. Positron particles are similar to beta particles except that they are positively charged. Thus, the positron can be considered a positively charged, high-speed electron which originates in the nucleus.

2. Orbital electron capture (K-capture) refers to the radioactive decay process whereby the nucleus captures an electron from an orbital shell of the atom. An electron from a higher energy level immediately moves in to fill the vacancy, and the excess energy is emitted as a characteristic x ray photon. The nucleus might conceivably capture an L-shell electron, but K-electron capture is much more probable. This mode of decay is frequently referred to as "K-capture." Orbital electron capture is generally abbreviated as "E.C."

Both positron emission and K-capture can be expected in nuclides with a low n:p ratio. The intranuclear effect of either mode of decay would be to change a proton into a neutron, thus increasing the n:p ratio.

3. Internal conversion occurs when a gamma photon does not escape the electron cloud surrounding the nucleus, but transfers to one of the orbital electrons enough energy to eject it from the atom. This process usually takes place in the K-shell. In principle, it is similar to the photoelectric effect.

4. Isomeric transition is a type of radioactive decay associated with certain pairs of nuclides that have the same mass number and the same atomic number, but different energy contents. Generally, one of the isomers of the pair is metastable and achieves ground state or a lower energy state by emitting delayed (usually greater than 10^{-9} seconds) gamma radiation. The metastable or excited state, therefore, represents one isomeric form of a particular nuclear species while the ground state represents the other. Generally, further radioactive decay by beta emission occurs from the ground state of the parent nuclide.

5. Neutrinos are neutral particles with negligible rest mass. They account for the energy distribution among beta particles in the beta-decay process from a given radionuclide.

D. Transmutation

When a radioactive nuclide decays by α, β^-, β^+ or K-capture, a transmutation occurs. The decay product--or "daughter"--has become an atom of a new element with chemical properties entirely unlike the original "parent" atom.

A nucleus emitting an alpha particle disintegrates to a daughter element, reduced in atomic number by 2 and reduced in atomic mass by 4; e.g., radium decays by alpha emission to produce radon as follows:

$$^{226}_{88}\mathrm{Ra} \rightarrow ^{222}_{84}\mathrm{Rn} + ^{4}_{2}\mathrm{He}$$

In beta emitters, the nucleus of the parent gives off a negatively charged particle, resulting in a daughter more positive by one unit of charge. The atomic number increases by one, but the mass number is unchanged; e.g., lead decays by beta emission to produce bismuth as follows:

$$^{214}_{82}\mathrm{Pb} \rightarrow ^{214}_{83}\mathrm{Bi} + ^{0}_{-1}\mathrm{e}$$

With positron emitters, the parent nucleus gives off a positive charge. This results in a daughter less positive by one unit of charge. The atomic number decreases by one and the mass number remains unchanged, as in the following reaction:

$$^{57}_{28}\mathrm{Ni} \rightarrow ^{57}_{27}\mathrm{Co} + ^{0}_{1}\mathrm{e}$$

If K-capture is the mode of decay, the transmutation resembles that of positron emission, as follows:

$$^{57}_{28}\mathrm{Ni} + ^{0}_{1}\mathrm{e} \rightarrow ^{57}_{27}\mathrm{Co}$$

Note that ^{57}Ni has two modes of decay. This is an example of the "branching" which is explained in the next section, Decay Phenomena.

Nuclear decay reactions resulting in a transmutation generally leave the resultant nucleus in an excited state. Nuclei, thus excited, may reach an unexcited or ground state by instantaneous emission of a gamma photon. All of the transmutation examples given would be accompanied by gamma emission. Although most nuclear decay reactions do have gamma emissions associated with them, there are numerous radionuclide species which decay by particulate emission with no gamma emission.

E. Decay Phenomena

Each radioactive nuclide, artificial and natural, has its own unique characteristic pattern of decay. There are two aspects associated with this "pattern"; one is the particular types and energies of the emissions involved, and the other is the rate of decay.

All nuclei of a given nuclide seeking stability by radioactive decay do so in a specific manner. As indicated, ^{226}Ra decays by an alpha emission which is accompanied by a gamma photon. This represents the only mode of decay open to ^{226}Ra. There are some radioactive nuclides which may decay with branching, whereby a choice of decay modes exists. In such case, a definite branching ratio exists. A case in point is the decay of ^{57}Ni. This isotope of nickel decays 50% by K-capture and 50% by β^+ emission. The branching ratio would be

$$\frac{\beta^+}{EC} = 1$$

Not only do various radionuclides disintegrate in a constant manner insofar as the types of emissions are concerned, but the emissions from each nuclide exhibit a distinct energy picture. The energies associated with radiations are given in terms of "million electron volts" (MeV). Beta emissions may occur with energies to about 5 MeV; alphas to about 10 MeV; and gamma photons to about 3 MeV. The energy of the particulate radiations is manifested as kinetic energy—the higher the energy the greater the velocity of the particle. However, the velocity of photons is constant (c = speed of light) and energy differences are manifested by varying wavelengths and frequencies.

The other characteristic aspect associated with decay patterns is the rate of decay. The disintegrations of radionuclides occur with a regularity characteristic for each particular species. Such disintegrations are spontaneous and random. A single radium nucleus, for instance, may disintegrate at once or wait thousands of years before emitting an alpha particle. All that can be predicted with any certainty is that half of all the ^{226}Ra nuclei present will disintegrate in 1622 years. This period is called the half-life of ^{226}Ra.

The wide range in half-life values for naturally occurring radionuclides is typified by ^{212}Po, with a half-life of 3×10^{-7} seconds, and ^{209}Bi, with a half-life of over 2×10^{18} years.

F. Radioactive Families

The transmutations associated with naturally occurring radionuclides frequently yield a daughter which also is radioactive. To date, about 70 different naturally occurring radionuclides have been identified, each with its own characteristic pattern of radioactivity. Most of these yield radioactive daughters and are now known to be intimately interrelated in radioactive series or families. It has been established that most isolated radioactive species belong to one of three independent groups or families. Each family starts with a parent radionuclide, decaying or transmuting into a radioactive daughter nuclide, which would again transmute into a daughter nuclide, also radioactive, and so on until stability is attained. One family starts with uranium-238 and is called the uranium series. Another starts with thorium-232 and is called the thorium series. A third starts with uranium-235 and is called the actinium series. Summaries of these series are found in Tables 1-3. In each series, there is a "seesawing" in the transmutation chain between decreasing the atomic number by two with α emission and increasing it by one with β emission. Each series ends in a different stable isotope of lead. There is also a fourth series, the neptunium series, named after its longest-lived member. (See Table 4.) Actually, the neptunium series has been artificially produced and does not occur in nature, but it is assumed that it did occur in nature at one time and has become extinct because of the relatively short half-lives involved. The longest-lived radionuclide in the series is $^{237}_{93}Np$ with a half-life of 2.2×10^6 years. Assuming the age of the earth is 2.2×10^9 years, this would indicate that, from the time of creation, ^{237}Np has undergone 1000 half-lives decay.

The fraction of a radionuclide remaining after 1000 half-lives would be fantastically small--in the order of 10^{-300}. It is obvious, therefore, why it would be difficult to find traces of neptunium and its descendants in nature.

G. Singly Occurring Radionuclides

Careful measurements show that almost all materials contain traces of radioactivity. One might suspect that these traces might be due to contamination with some of the heavy radionuclides belonging to one of the radioactive series described. However, some of the lighter elements are themselves weakly radioactive. Table 5 lists five examples of naturally occurring radionuclides and their radiations.

Currently, there is no evidence that any series relationship exists among these nuclides. Therefore, they are regarded as individual, naturally occurring radionuclides with no familial relationships.

IV. ARTIFICIAL RADIOACTIVITY

As implied in the nomenclature, natural and artificial radioactivity differ in origin. There are other distinctions between the two types which will be discussed. Nevertheless, the nuclei of artificial radionuclides are unstable in much the same manner as their natural counterparts. The intranuclear factors governing decay are also similar for both groups.

A brief account of the discovery of artificial radioactivity will be given before further discussing its similarities and dissimilarities to natural radioactivity.

A. Induced Transmutations

In 1919, Lord Rutherford demonstrated that it was possible to produce artificially a transmutation of elements. How naturally occurring unstable or radioactive atoms are transmuted by ejecting ionizing particles and rays has been discussed. Lord Rutherford set up and observed a nuclear reaction in reverse, one might say, whereby high-speed charged particles (projectiles) bombarded stable atomic nuclei (target), resulting in a reaction at the nuclear level and inducing a transmutation. The first observed nuclear reaction used alpha particles from ^{214}Bi (RaC) as the charged particles. These were made to impinge upon nitrogen nuclei, acting as the target. The reaction is written as follows:

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$$

Since the discovery of the transmutation of nitrogen, many hundreds of artificial or induced transmutations have been found. Until 1932, most induced transmutations were performed utilizing naturally occurring alpha emitters as sources of incident particles. With the development of particle accelerators, other bombarding particles have been successfully used. No attempt will be made here to catalog the many kinds of possible transmutations, nor will any attempt be made to discuss the theory and quantitative data regarding nuclear reactions.

B. Induced Radioactivity

During the first 15 years of experimental work with nuclear reactions, the transmutation products (insofar as could be observed)

TABLE 1.--The Uranium Series

Radioelement	Corresponding Element	Symbol	Radiation	Half Life
Uranium I	Uranium	^{238}U	α	4.51 x 10^9 y
Uranium X_1	Thorium	^{234}Th	β	24.1 d
Uranium X_2 *	Protactinium	^{234}Pa	β	1.18 m
Uranium II	Uranium	^{234}U	α	2.48 x 10^5 y
Ionium	Thorium	^{230}Th	α	8.0 x 10^4 y
Radium	Radium	^{226}Ra	α	1.62 x 10^3 y
Ra Emanation	Radon	^{222}Rn	α	3.82 d
Radium A 99.98% | 0.02%	Polonium	^{218}Po	α and β	3.05 m
Radium B	Lead	^{214}Pb	β	26.8 m
Astatine-218	Astatine	^{218}At	α	2 s
Radium C 99.96% | 0.04%	Bismuth	^{214}Bi	β and α	19.7 m
Radium C'	Polonium	^{214}Po	α	1.6 x 10^{-4} s
Radium C"	Thallium	^{210}Tl	β	1.32 m
Radium D	Lead	^{210}Pb	β	19.4 y
Radium E 100 % | 2 x 10^{-4}%	Bismuth	^{210}Bi	β and α	5.0 d
Radium F	Polonium	^{210}Po	α	138.4 d
Thallium-206	Thallium	^{206}Tl	β	4.20 m
Radium G (End Product)	Lead	^{206}Pb	Stable Stable	—

* Undergoes isomeric transition to form uranium Z (^{234}Pa); the latter has a half life of 6.7 h, emitting β radiation and forming uranium II (^{234}U).

TABLE 2.--The Thorium Series

Radioelement	Corresponding Element	Symbol	Radiation	Half Life
Thorium	Thorium	^{232}Th	α	1.39 x 10^{10} y
Mesothorium I	Radium	^{228}Ra	β	6.7 y
Mesothorium II	Actinium	^{228}Ac	β	6.13 h
Radiothorium	Thorium	^{228}Th	α	1.91 y
Thorium X	Radium	^{224}Ra	α	3.64 d
Th Emanation	Radon	^{220}Rn	α	52 s
Thorium A	Polonium	^{216}Po	α	0.16 s
Thorium B	Lead	^{212}Pb	β	10.6 h
Thorium C 66.3% | 33.7%	Bismuth	^{212}Bi	β and α	60.5 m
Thorium C'	Polonium	^{212}Po	α	3 x 10^{-7} s
Thorium C"	Thallium	^{208}Tl	β	3.1 m
Thorium D (End Product)	Lead	^{208}Pb	Stable	—

TABLE 3.--The Actinium Series

Radioelement	Corresponding Element	Symbol	Radiation	Half Life
Actinouranium	Uranium	^{235}U	α	7.13 x 10^8 y
Uranium Y	Thorium	^{231}Th	β	25.6 h
Protactinium	Protactinium	^{231}Pa	α	3.43 x 10^4 y
Actinium 98.8% | 1.2%	Actinium	^{227}Ac	β and α	21.8 y
Radioactinium	Thorium	^{227}Th	α	18.4 d
Actinium K	Francium	^{223}Fr	β	21 m
Actinium X	Radium	^{223}Ra	α	11.7 d
Ac Emanation	Radon	^{219}Rn	α	3.92 s
Actinium A ~100% | ~5 x 10^{-4}%	Polonium	^{215}Po	α and β	1.83 x 10^{-3} s
Actinium B	Lead	^{211}Pb	β	36.1 m
Astatine-215	Astatine	^{215}At	α	~10^{-4} s
Actinium C 99.7% | 0.3%	Bismuth	^{211}Bi	α and β	2.16 m
Actinium C'	Polonium	^{211}Po	α	0.52 s
Actinium C"	Thallium	^{207}Tl	β	4.78 m
Actinium D (End Product)	Lead	^{207}Pb	Stable	—

TABLE 4.--The Neptunium Series

Element	Symbol	Radiation	Half Life
Plutonium	^{241}Pu	β	13.2 y
Americium	^{241}Am	α	462 y
Neptunium	^{237}Np	α	2.20 x 10^6 y
Protactinium	^{233}Pa	β	27.4 d
Uranium	^{233}U	α	1.62 x 10^5 y
Thorium	^{229}Th	α	7.34 x 10^3 y
Radium	^{225}Ra	β	14.8 d
Actinium	^{225}Ac	α	10.0 d
Francium	^{221}Fr	α	4.8 m
Astatine	^{217}At	α	1.8 x 10^{-2} s
Bismuth 98% | 2%	^{213}Bi	β and α	47 m
Polonium	^{213}Po	α	4.2 x 10^{-6} s
Thallium	^{209}Tl	β	2.2 m
Lead	^{209}Pb	β	3.32 h
Bismuth (End Product)	^{209}Bi	Stable	—

TABLE 5.--Naturally Occurring Radionuclides

Nuclide	Half-Life	Emission Energies in MeV		
		Alpha	Beta	Gamma
$^{40}_{19}K$	1.26×10^{9} y	---	1.314	1.460
$^{87}_{37}Rb$	5.0×10^{10} y	---	0.274	---
$^{147}_{62}Sm$	1.05×10^{11} y	2.23	---	---
$^{176}_{71}Lu$	3.0×10^{10} y	---	0.43	.088 .202 .306
$^{187}_{75}Re$	4.0×10^{10} y	---	.003	.134

were not radioactive. However, the reactions generally were accompanied by the emission of a charged particle and a gamma ray. These emissions are not construed as imparting the property of radioactivity to the target element, since they occur practically instantaneously.

It was determined in 1934 that induced transmutations could produce nuclei which were residually unstable in somewhat the same manner as naturally occurring radionuclides. Madame Curie and M. Joliot reported that certain light elements (boron, magnesium, aluminum), when bombarded with alpha particles continued to emit radiation for a finite time after bombardment had stopped. The following reaction, involving aluminum bombarded with alpha particles, was the first reported instance of induced or artificial radioactivity:

$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

The resultant nucleus $^{30}_{15}P$ was observed to be radioactive, decaying by β^{+} emission with a half-life of 2.6 minutes.

The work of Curie and Joliot stimulated similar experiments throughout the world. As a result, radioactive isotopes of nearly every element in the Periodic Table were produced by bombarding a stable isotope with charged particles, neutrons, or, in certain instances, photons. Over 1,000 unstable nuclear species are listed in the Table of Isotopes(1).

It may have been noted that carbon-14 was not included as a natural radionuclide even though it has received considerable popular attention in recent years as "naturally" occurring elemental carbon in definite, though small, proportions. The ^{14}C existing in the atmosphere is being formed continually as a result of nuclear reactions between atmospheric nitrogen and neutrons from cosmic rays. This is shown in the following reaction:

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

Naturally occurring radionuclides, in becoming stable, generally emit beta or alpha particles by a series of transmutations. Artificial radionuclides rarely decay by alpha emission; they usually decay by β^{-}, β^{+} emission or orbital electron capture. In contrast to natural radioactivity, induced radionuclides generally revert to stability in a single decay step.

C. Fission Products

Another source of radionuclides is nuclear fission. The nuclear fragments directly resulting from fission invariably have too large a proportion of neutrons to protons for stability, and consequently tend to achieve stability by negative beta emission. Each nuclear fragment initiates a radioactive series (fission decay chain) involving the successive emission of beta particles. Fission product beta emission, as with other beta emitters, generally is accompanied by gamma emission.

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GPO 892-446

Interaction Of Radiation With Matter

I. INTRODUCTION

A. All radiation possesses energy either inherently, as in the case of electromagnetic radiation, or as kinetic energy of motion in the case of the particulate radiations. Absorption of radiation is the process of transferring this energy to atoms of the medium through which the radiation is passing. To say that radiation interacts with matter is to say that it is either scattered or absorbed. The mechanisms of the absorption of radiation are of fundamental interest in the field of radiological health primarily because of the following reasons:

1. Absorption in body tissues may result in physiological injury.

2. Absorption is the principle upon which detection is based.

3. The degree of absorption or type of interaction is a primary factor in determining shielding requirements.

B. The transfer of energy from the emitted particle or photon to atoms of the absorbing material may occur by several mechanisms but, of the radiations commonly encountered, the following two are the most important:

1. Ionization--any process which results in the removal of an electron (negative charge) from an atom or molecule thereby leaving the atom or molecule with a net positive charge.

2. Excitation--the addition of energy to an atomic or molecular system, thereby transferring it from its ground state to an excited state. Depending on the type of interaction, either the atomic nucleus or one of its orbital electrons may absorb the excitation energy.

C. Ordinarily, the atoms in a material are electrically neutral, i. e., they have exactly as many negative electrons in orbit as there are positive protons in the nucleus. Thus the difference, or net electrical charge, is zero. Radiations have the ability to either tear loose one or more of the electrons from their orbit or raise the orbital electrons to a higher energy level. In the former case (ionization) there is left behind an atom carrying an excess of positive charge, and a free electron. In the latter case (electronic excitation), the excited atom may lose its excess energy when an electron in a higher energy shell falls into the lower energy vacancy created in the excitation process. When this occurs, the excess energy is liberated as a photon of electromagnetic radiation (which may escape from the material but usually undergoes other absorptive processes.) Nuclear excitation is of significance only for neutrons or other radiation of relatively high energies. A discussion of the types of radiations and their interactions might conveniently be divided into four main categories:

1. Heavy, positively charged particles: alpha particles, protons, deuterons, tritons, and possibly mesons, would exhibit similar mechanisms of interaction with matter.

*Alpha particles will be discussed as a prototype of this group.

2. Beta particles: Both positions and electrons would fall into this category. They have equal masses and equal but opposite charges, and therefore lose their kinetic energy by similar mechanisms. The electron is used as the prototype of this category.

3. Electromagnetic radiation: This group includes both x- and gamma radiation; however since these two radiations differ in their origin and not in their mechanism of interaction, only gamma radiation will be discussed.

4. Neutrons: The interaction of neutrons is discussed separately in another section of this manual. Therefore, to avoid duplication, this radiation will not be described herein.

II. ALPHA ABSORPTION

A. An alpha particle is made up of two protons (positively charged) and two neutrons, all strongly bound together by nuclear forces. If such a particle approaches an electron (negatively charged), it experiences a strong electrostatic attraction, whereas if it approaches an atomic nucleus (also positively charged) it will tend to be repelled. Alpha particles have a mass about 8,000 times that of the electron. They are ejected from the nuclei of radioactive atoms with velocities of the order of 1/20 the speed of light. All of these properties--its large mass, its charge, and its high velocity tend to make the alpha particle an efficient projectile when it encounters atoms of an absorbing material. In other words, it would have a high probability of interacting, or colliding, with orbital electrons, and also atomic nuclei.

B. When speaking of "collisons" between subatomic particles, it should be understood that the particles (for example an alpha and an atomic nucleus) need approach each other only sufficiently close for forces to interact. Such an interaction may then be referred to as an collision. An alpha may undergo either elastic (no transfer of energy), or inelastic (transfer of energy from the alpha radiation to the target particle) collisions.

Inelastic collisions may result in ionization and/or excitation. And since a finite amount of energy is required to ionize or excite an atom, the kinetic energy of the alpha particle is gradually dissipated by such interactions until it captures two electrons and settles down to a quiet existance as a helium atom.

C. Due to the high probability of interaction between an alpha particle and orbital electrons of the absorbing medium, a large number of ion pairs are formed per unit path length. And since a fraction of the kinetic energy of the alpha particle is absorbed on formation of each ion pair, this type of radiation loses its energy over a relatively short distance. For these reasons, the range of alpha particles is much less than the range of other forms of radiation. It is, in summary a highly ionizing, weakly penetrating radiation.

1. Alpha particles from a given radionuclide are all emitted with the same energy, consequently those emitted from a given source will have approximately the same range in a material. Alpha particle range is usually expressed in centimeters of air.

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*Due to their large mass, heavier particles, such as fission fragments, would lose energy predominantly by other processes.

The relationship between range and energy has been expressed empirically as follows:

$$R_a = 0.318\ E^{3/2}$$

Where:

R_a = range in cm. of air at 1 atm. and 15° C

E = energy in Mev

The range of alpha radiation in solids may be compared to their range in air. The approximate relationship between range in a solid and range in air is given below:

$$R_{solid} = \frac{3.2\ \ 10^{-4} R_{air} \sqrt{A_{solid}}}{\rho_{solid}}$$

R = range

ρ = density

A = mass number

2. The number of ion pairs formed per centimeter of path in any given medium is called the specific ionization for that particular ionizing radiation.

$$\text{Specific ionization} = \frac{\text{number of ion pairs formed}}{\text{Centimeters of path}}$$

3. About 34 electron volts of energy are required for the formation of a primary ion pair in air. Only about half to two-thirds of this is required to remove the orbital electron, the balance being lost in electronic excitation processes. Depending on the energy of the alpha particle, the number of ion pairs formed per centimeter of path in air will range from 5,000 to 80,000.

III. BETA ABSORPTION

The rest mass of a beta particle is the same as that of an orbital electron and, as a consequence, very much smaller than the mass of the nuclei of the atoms making up the absorbing medium. Since beta particles and orbital electrons have like charges, they experience an electrostatic repulsion when in the vicinity of one another. But a beta particle has a charge opposite to that on the atomic nucleus, therefore an electrostatic attraction will be experienced as the beta approaches the nucleus.

All of these factors must be realized in order to understand the interaction between the beta radiation and atoms in an absorbing medium. For example, considering only the mass relationship between the beta particles and orbital electrons, one might expect that the interaction between these two electrons is somewhat similar to the collisions between billiard balls.

Actually, a beta particle may lose all of its energy in a single collision. In such an interaction, the target electron can effectively become an ionizing particle.

Normally a beta particle loses its energy in a large number of ionization and excitation events in a manner analogous to the alpha particle. Due to the smaller size and charge of the electron, however, there is a lower probability of beta radiation interacting in a given medium; consequently, the range of a beta is considerably greater than an alpha of comparable energy.

Since the electronic mass is small compared with that of a nucleus, large deflections can occur in single collisions, particularly when electrons of low ene[illegible] les are scattered by high atomic number elements (high positive charge on the nucleus). As a result, a beta usually travels a tortuous, winding path in an absorbing medium.

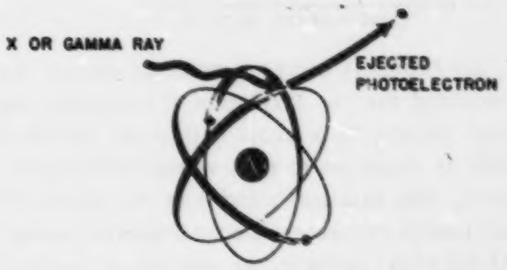
In addition to ionization and excitation, a beta may have an interaction with an atom which results in the production of x-rays. A high energy beta may penetrate through the electron cloud surrounding the nucleus of the atom, and in traveling through the various quantum energy states of the orbital electrons, it experiences the strong electrostatic force of the nucleus, resulting in a change in velocity and the emission of several x-rays having a spectrum of energies. (Such x-rays are referred to as "Bremsstrahlung radiation"). It becomes an increasingly important mechanism of energy loss as the initial energy of the beta increases, and the atomic number of the absorbing medium increases. As previously pointed out, all alpha particles from a given radionuclide are emitted with the same energy. When betas are emitted, the total kinetic energy involved in the decay of the radioactive atom is divided between the beta and neutrino. The neutrino has a zero charge and negligible mass, consequently its contribution to the overall interaction is insignificant, but it does carry away a fraction of the total kinetic energy available, therefore the beta may be emitted with an energy varying from practically zero up to a maximum energy (which is a characteristic of the particular radionuclide).

IV. GAMMA ABSORPTION

X- and gamma rays differ only in their origin, and an individual x-ray could not be distinguished from an individual gamma ray. Both are electromagnetic waves, or quanta, and differ from radio waves and visible light waves only in having much shorter wavelengths. The difference in name is used to indicate a difference in source--gamma rays are of nuclear origin, while x-rays are of extra-nuclear origin (i.e., they originate in the electron cloud surrounding the nucleus). Both x-rays and gamma rays have zero rest mass, no net electrical charge, and travel with the speed of light. They are basically only distortions in the electromagnetic field of space, and because of this fact, they interact electrically with atoms to produce ionization even though they themselves possess no net electrical charge. As previously pointed out, gamma rays will be discussed as the prototype of this type of radiation. There are three mechanisms by which gamma rays lose energy by interacting with matter.

A. The Photoelectric Effect

The photoelectric effect is an all-or-none energy loss. The gamma wave, or photon, imparts all of its energy to an orbital electron of some atom. The gamma photon, since it consisted only of energy in the first place, simply vanishes. The energy is imparted to the orbital electron in the form of kinetic energy of motion, and this greatly increased energy overcomes the attractive force of the nucleus for the electron and causes the electron to fly from its orbit with considerable velocity. Thus, an ion-pair results. The high velocity electron (which is called a photoelectron) has sufficient energy to knock other electrons from the orbits of other atoms, and it goes on its way producing secondary ion-pairs until all of its energy is expended.

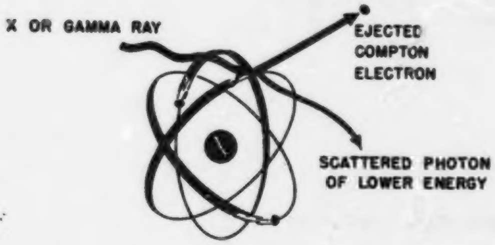


PHOTOELECTRIC EFFECT
(PRIMARILY LOW ENERGY PHOTON)

Figure 1a

B. The Compton Effect

The Compton Effect provides a means of partial energy loss for the incoming gamma ray. Again the gamma ray appears to interact with an orbital electron of some atom, but in the case of Compton interactions, only a part of the energy is transferred to the electron, and the gamma ray "staggers on" in a weakened condition. The high velocity electron, now referred to as a Compton electron, produces secondary ionization in the same manner as does the photoelectron, and the weakened gamma ray continues on until it loses more energy in another Compton interaction or disappears completely via the photoelectric effect. The unfortunate aspect of Compton interaction is that the direction of flight of the weakened gamma ray is frequently referred to as a "scattered" photon, and the entire process known as "Compton scattering". By this mechanism of interaction, the direction of photons in a beam may be randomized, so that scattered radiation may appear around corners and behind "shadow" type shields.



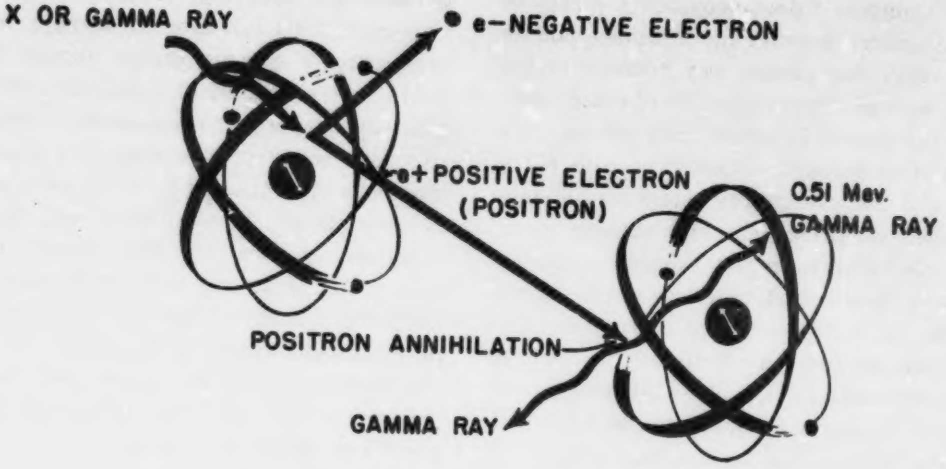
COMPTON EFFECT
(PRIMARILY MEDIUM ENERGY PHOTON)

Figure 1b

C. Pair Production

Pair production, the third type of interaction, is much rarer than either the photoelectric or Compton effect. In fact, pair production is impossible unless the gamma ray possesses at least 1.02 Mev of energy. (Practically speaking, it does not become important until two Mev of energy). In pair production a gamma photon simply disappears in the vicinity of a nucleus, and in its place appears a pair of electrons--one negative, one positive. The mass of these electrons has been created from the pure energy of the photon, according to the familiar Einstein equation $E = mc^2$, where (E) is energy, in ergs, (m) in mass in grams, and (c) is the velocity of light in cm/sec. If there is any excess energy in the photon above the one Mev required to create two electron masses, it is simply shared between the two electrons as kinetic energy of motion, and they fly out of the atom with great velocity. The negative electron behaves in exactly the ordinary way, producing secondary ion-pairs until it loses all of its energy of motion. The positive electron (known as a positron) also produces secondary ionization so long as it is in motion, but when it has lost its energy and slowed almost to a stop, it encounters a free (negative) electron somewhere in the material. The two are attracted by their opposite charges, and upon contact, annihilate each other, converting the mass of each into pure energy. Thus two gammas of 0.51 Mev arise at the site of the annihilation. The ultimate fate of the annihilation gammas is either photoelectric absorption or Compton scattering followed by photoelectric absorption.

Figure 1 illustrates the three mechanisms of gamma interaction, and Figure 2 shows the fraction of the total decrease in beam intensity which is due to the action of each, for energies between 10 kev and 100 Mev, using lead as the absorbing material. At low energies the photoelectric interactions predominate, at intermediate energies Compton scattering is the most likely interaction, and at high energies pair production is the most important.


X OR GAMMA RAY
e−NEGATIVE ELECTRON
e+POSITIVE ELECTRON
(POSITRON)
0.51 Mev.
GAMMA RAY
POSITRON ANNIHILATION
GAMMA RAY

PAIR PRODUCTION

(HIGH ENERGY PHOTON, > 1.02 Mev.)

Figure 1c

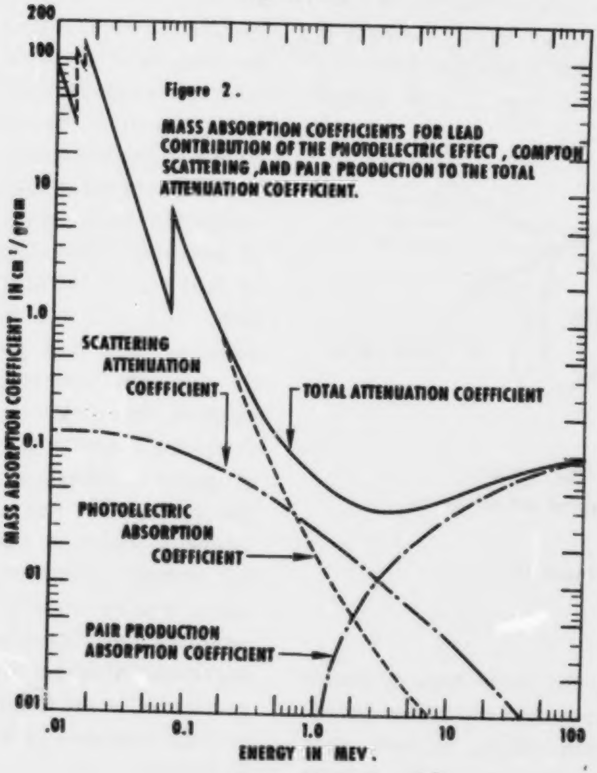


Figure 2

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GPO 891-761

Units of Radioactive Decay and the Decay Law

I. INTRODUCTION

The most widely used unit of quantity of radioactive material is the curie.

II. THE CURIE UNIT

A. Original Definition

Originally, the curie unit applied only to radium. It was based on the disintegrations per second occurring in the quantity of radon gas in equilibrium with one gram of radium. If permitted to attain this equilibrium, one gram of radium will produce about 0.66 mm^3 of radon. In this quantity of radon, about 37 billion atoms disintegrate each second.

B. Later Modifications

The International Radium Standard Commission extended the definition in 1930 to include that quantity of any radioactive decay product of radium which underwent the same number of disintegrations per second as one gram of radium. It avoided specifying the figure exactly, so for some years the exact value of the curie unit varied with each successive refinement in the measurement of the decay constant or the atomic weight of radium.

C. Modern Practice

In 1950, the International Joint Commission on Standards, Units, and Constants or Radioactivity redefined the curie unit by accepting 37 billion disintegrations per second as a curie of radioactivity regardless of its source or characteristics. At present, the unit of quantity of radioactivity, the curie, merely requires that in the given sample of any material, 3.7×10^{10} disintegrations occur each second. Smaller--and often more convenient--units are the millicurie, (one-thousandth of a curie: mCi), and the microcurie, (one-millionth of a curie: μCi). The picocurie (3.7×10^{-2} dis/sec or 2.22 dis/min) is often used to express the very low natural and environmental levels.

D. Curies and Grams: Specific Activity

The term curie originated from the number of emanations from one gram of radium. Thus, the activity of one gram of radium is equivalent to one curie. It is important, however, to note that when applied to radionuclides other than radium, the curie unit does not make apparent what weight of the material is required. Since the curie of activity is 37 billion disintegrations per second, the weight of the material required to produce this number of disintegrations per second will be a function of the decay rate of the atoms of the material (i.e., the disintegration constant) and of the number of atoms of the material per gram (i.e., gram atomic weight). As examples, a curie of pure ^{60}Co would weigh less than 0.9 milligram, whereas a curie of natural ^{238}U would require over two metric tons of the metal. "Curies per gram" is termed "specific activity."

III. THE RADIOACTIVE DECAY LAW

A. The Disintegration Constant

The activity of any sample of radioactive material decreases or decays at a fixed rate which is a characteristic of that particular radionuclide. No known physical or chemical agents (such as temperature, pressure, dissolution, or combination) may be made to influence this rate. The rate may be characterized in at least two ways, one of which is the use of the disintegration constant (λ). The disintegration constant (λ) represents the fraction of the total number of atoms present which decays in a unit time. Thus the number of disintegrations occurring per unit time in a given sample is the product of the number of atoms present in the sample, (N), and the fraction of these disintegrating in each unit time, (λ), or:

$$-\frac{dN}{dt} = \lambda N$$

where the minus sign is used to indicate that the number of atoms is diminishing. Integration of the above equation leads to the basic law of radioactive decay:

$$N_t = N_0 e^{-\lambda t}$$

Written out, this equation reads: the number of atoms (N_t) remaining after a time (t) is equal to the original number (N_0) multiplied by $e^{-\lambda t}$, where (e) is the base of the natural system of logarithms and (λ) is the disintegration constant.

B. The Half-Life

The disintegration constant is not as convenient as another method of representing the rate of radioactive decay. This is the half-life, or $T_{½}$, of the radionuclide. It is the length of time required for one half of the original number of nuclei to disintegrate. The relationship of the half-life to the disintegration constant (λ) can be shown in the following way:

$$\lambda = \frac{0.693}{T_{½}}$$

Therefore, one may substitute this expression for (λ) in the basic decay law, and

$$N_t = N_0 e^{-\frac{0.693\,t}{T_{½}}}$$

If it is desired to have the equation in terms of activity instead of number of atoms, one can multiply both sides of the equation by the disintegration constant (λ) as follows:

$$\lambda N_t = N_0 e^{-\frac{0.693\,t}{T_{½}}}$$

but $\lambda N = A$

therefore:

$$A_t = A_0 e^{-\frac{0.693\,t}{T_{½}}}$$

This is the working equation for computing the amount of radionuclide which will remain from the original sample after an interval of time elapses.

C. Computational Method

Example:

Given: $A_0 = 10$ mCi of ^{32}P

$t = 120$ days

$T_{½} = 14.2$ days(1)

Find A_t the quantity remaining after 120 days

$$A_t = (10)\, e^{-\frac{(0.693)(120)}{14.2}}$$

$$= 10\, e^{-5.85} = 10\,(0.00288)$$

$$A_t = 0.0288 \text{ mCi}$$

This is the sort of calculation which would be required before diluting a radioisotope for future use or for determining the remaining activity in a quantity of nuclide which had been stored for some time since its standardization.

D. Graphic Method

There is an easy graphical method of accomplishing this same computation. It is based on the relation that each successive half-life reduces the activity present by one-half, and the effect is cumulative: i.e., two half-lives reduce to ½ × ½ or ¼; three reduce to ½ × ½ × ½ or ⅛, etc. In the general case,

$$A_n = A_0(\tfrac{1}{2})^n$$

where (n) is the number of half-lives elapsed. This function is graphed in the Radiological Health Handbook under Radioactive Decay, Semi-Log Plot. The answer to the "example" problem may easily be read from the graph at the point where the line intersects the horizontal axis. This number (8.44) is the number of half-lives of ^{32}P in a 120-day period. A useful "rule of thumb" to remember is that seven half-lives will reduce any activity to below 1 percent of its original value.

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Quantities and Units of Radiation

I. INTRODUCTION

The structure and meaning of currently accepted definitions used in quantitative determination of radiation fields must be understood. Without a physically consistent, realistic, and measurable description of the radiation field, the clinician, radiologist, or technologist could not utilize radiation with reproducibility or safety, nor could the effects of radiation on living organisms be ascertained. The concepts discussed in this outline represent only part of a set of radiation quantities and units established by the International Commission on Radiation Units and Measurements (ICRU) in its Report Number 11, Radiation Quantities and Units, published in 1968.

II. QUANTITIES AND UNITS

The ICRU has standards which clearly delineate radiation quantities and radiation units.

A "quantity" may be thought of as a description of a physical concept or principle. The magnitude or measure of a quantity is a "unit." Fundamentally, therefore, the quantity is the more important. The unit places limits upon, but will not serve to define, the quantity. For example, the concept of length is a quantity; the meter is a unit of length.

An internationally accepted system of writing and abbreviating units has been established. To avoid confusion with the name of the man for whom a unit may be named, the name is capitalized when referring to the man (Roentgen) but when referring to the unit, the name will be written in lower case (roentgen).

The abbreviation for the unit is, however, capitalized (R). In cases where the abbreviation conflicts with another accepted symbol, a combination of letters, usually the first and last, is used. An illustration is seen in the case of the unit curie. The abbreviation used is Ci, as other possible symbols conflict with the symbol for coulomb and with common chemical symbols.

A. Radiation Quantities

Radiation may be divided into two classes: ionizing and non-ionizing. X rays, for example, are classified as ionizing radiations by virtue of their energy. Ionizing radiations, however, include many types of radiations in addition to x rays. The ICRU has considered ionizing radiations in two categories:

1. Directly ionizing particles or charged particles (electrons, protons, alpha particles, etc.), which have sufficient kinetic energy to cause ionization by collision; and
2. Indirectly ionizing particles or uncharged particles (neutrons, gamma rays, x rays, etc.), which can interact and liberate directly ionizing particles.

Quantities describing the effects of the interaction of directly and indirectly ionizing radiations with matter have been developed to cover many aspects of the interaction processes. For practical radiation protection measurements and control, only four quantities are generally utilized. These will be discussed in greater detail in the following material.

B. Exposure

Historically, the most important term associated with radiation exposure has been the roentgen. So, after a series of redefinitions, the roentgen has been chosen as the unit for the quantity exposure. The current definition of exposure is:

> The exposure (X) is the quotient of ΔQ by Δm, where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons), liberated by photons in a volume element of air whose mass is Δm, are completely stopped in air.

$$X = \frac{\Delta Q}{\Delta m}.$$

Several important restrictions applying to the quantity are immediately apparent from the wording of the definition:

1. The medium in which exposure is defined is air; no other medium is acceptable.
2. The radiations for which exposure is defined are photons (x ray and gamma).
3. The effect being measured is ionization of the air.
4. All electrons liberated in the ionizing processes must be stopped in air.

The last restriction serves to impose upper limits on the maximum quantum energy which may be directly measured in terms of exposure, because the range of the electrons liberated increases as a function of the energy. A chamber (see a discussion of the free air chamber) which measures exposure directly must have dimensions such that the distances from the electrodes to the sites of interaction are greater than the maximum range of the secondary electrons. For example, a chamber intended to measure exposure resulting from a beam of 2 MeV photons would require overall dimensions greater than 15 meters, because the maximum range in air of 2 MeV electrons which may be liberated is on the order of 7.5 meters.

The meaning of the symbol Δ (read delta) is best illustrated by considering the fact that the interaction of radiation is not continuous. Interaction locations are discrete sites which can only be described statistically. If the measuring volume is too small, a single measurement of the effect may include no interaction or, through chance, several interactions may have occurred within the volume. Therefore, an average value must be determined. This effect of random variations obtained by a series of measurements is shown in the left region of the curve in Figure 1. As the volume is increased, the effect of the larger volume is to average the effects measured in a series of smaller volumes. The result approaches closely the true average, as indicated in the center portion of the curve. A continued increase in the volume would now include regions outside the radiation field, and the measured values would decrease, as shown on the right. In short, the measurement of radiation fields involves statistical averaging procedures; the symbol Δ will precede the symbols for quantities that may be involved in such averaging procedures.

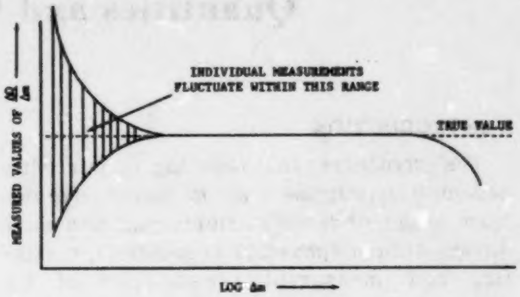

Figure 1.--Detector Response vs. Volume

C. Absorbed Dose

Exposure, as noted earlier, is limited to measurement of the ionization in air produced by x or γ radiations. This quantity is, of course, extremely limited: Many types of radiation exist, and the material of interest in which interaction occurs in most cases is not air. Additionally, ionization produced by the radiation may not be the effect which is most usefully evaluated. "Absorbed dose" is a quantity much more general in its structuring. It is defined as follows:

> The absorbed dose (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted

by ionizing radiation to the matter in a volume element, and Δm is the mass of the matter in that volume element.

$$D = \frac{\Delta E_D}{\Delta m}.$$

The following points are to be seen in the definition:

1. Any type of ionizing radiation (directly or indirectly ionizing) is included.
2. Any material may be used in making the measurement.
3. The effect observed is the energy imparted by the radiation to the matter in the volume element.

Most often a direct measurement of absorbed dose will be carried out by calorimetry, since temperature changes--which directly reflect the energy input to the mass (if one excludes possible changes from associated chemical energies)--are relatively easy to measure. Again, it must be pointed out that selection of the size of the mass is important as statistical averaging procedures apply.

The energy imparted to the matter in the volume element is not necessarily equal to the amount of energy removed from the beam. Secondary electrons, for example, may carry some energy to matter in adjacent volumes. The energy lost is related to another quantity, "kerma" (kinetic energy released in material).

Because absorbed dose is a general quantity applying to any radiation in any material, it could certainly be applied to x radiation in air. Thus a relation between absorbed dose and exposure may be established in air or in other media.

D. Dose Equivalent

Research has shown that the effect of ionizing radiations on biological systems is not related exclusively to absorbed dose. The effects observed depend on many factors and include:

1. Type of radiation
2. Energy of the radiation
3. Distribution and/or fractionation of the radiation
4. Biological endpoint chosen
5. Time at which the endpoint is evaluated
6. Species and strain of the organism utilized.

Many other factors, such as the administration of certain drugs, also influence the response to radiation. In an effort to provide a comparable numerical basis for the effects of various types of radiation for protection purposes, a quantity termed the "dose equivalent" (DE) has been defined as:

> The product of the absorbed dose (D), quality factor (QF), and other necessary modifying factors:

$$DE = D\ (QF)\ (\ .\ .\ .\ ).$$

Depending upon the effect chosen for evaluation, the result obtained when the effects of two types of radiation are compared (frequently termed in radiobiological research the "relative biological effectiveness" or RBE) may vary widely. A representative value for the RBEs is selected by a committee to be used for radiation protection purposes. This value is termed the "quality factor" (QF).

Typical quality factors, given here, are taken from Rees, D. J., Health Physics: Principles of Radiation Protection (London: Butterworth, 1967):

Quality Factor	Type of Radiation
1.0	X rays; γ rays; electrons; and β rays with E_{max} greater than 0.03 MeV
1.7	β rays with E_{max} not greater than 0.03 MeV
10.*	Neutrons and protons up to 10 MeV
10.	Naturally occurring α particles
20.	Heavy recoil nuclei

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*30, in the case of irradiation of the eyes.

E. Activity

A quantity is necessary to describe the rate at which a radionuclide undergoes nuclear transformations. Historically, radium was used as a standard, but ICRU recommendations have established a quantity which is independent of any particular substance and depends only on measurable quantities, i.e., the number of transformations occurring and the time during which these emissions took place. The quantity involved is "activity" and is defined as follows:

> The activity (A) of a quantity of a radioactive nuclide is the quotient of ΔN by Δt where ΔN is the number of nuclear transformations which occur in this quantity in time Δt.
>
> $$A = \frac{\Delta N}{\Delta t}.$$

Activity applies only to the number of nuclear transformations taking place per unit time and is not directly related to the exposure rate, absorbed dose rate, or dose equivalent rate due to the radionuclide.

F. Units

Each of the quantities discussed has a measure or "unit" assigned to it. Exposure is expressed in terms of the equation

$$X = \frac{\Delta Q}{\Delta m},$$

where Q represents electrical charge (produced by ionization) per unit mass of air. Hence, any units of charge over mass would conform with the definition. The ICRU has, however, established a special unit, the use of which is restricted to measurement of exposure only. The unit of charge used is the "coulomb," and the unit mass is the "kilogram." Specifically,

$$1 \text{ roentgen} = 2.58 \times 10^{-4} \text{ coulombs/kilogram}^{*}$$

Absorbed dose, defined in terms of energy deposited in a mass, would demand units of energy (joules, for example) per unit mass (kilograms). Again, a special unit has been defined which is used in referring to absorbed dose:

$$1 \text{ rad} = {}^{1}/_{100} \text{ joule/kilogram} = 100 \text{ ergs/gram.}$$

The unit of dose equivalent is the "rem," which is obtained by multiplying the dose in rads by the appropriate quality factor and other modifying factors. The ICRU notes in its report that this statement ". . . does not cover a number of theoretical aspects (in particular the physical dimensions of some of the quantities) . . . " but that " . . . it fulfills the immediate requirement for an unequivocal specification of a scale that may be used for numerical expression in radiation protection." In short, since dimensionality is ignored, rems = rads × QF. Since the QF for x and gamma radiation is 1, the number of rems is identical to the absorbed dose in rads for these radiations.

The special unit for activity is the "curie." The commission has recommended that steps be taken to redefine the curie as

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ s}^{-1} \text{ (exactly).}$$

The earlier definition of the curie was based on the activity of the radon gas in equilibrium with one gram of radium. Recent measurements have shown that the activity associated with this standard is $3.61 \times 10^{10} \text{ s}^{-1}$ and hence the unit has been redefined as a number independent of any given radioactive nuclide.

III. PRACTICAL CONSIDERATIONS

In the application of instrumentation to the assessment of the radiation fields, care must be taken to select instruments which will truly indicate or measure the radiation quantity of interest. Exposure can only be measured directly by an air-filled device which measures ionization in air. In practice, most exposure measuring instruments are related to a free-air chamber, and do not actually measure exposure directly. Most of the ionization produced and measured originates in the chamber wall--which is hopefully an "air equivalent" material.

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*The magnitude of this unit does not differ from the magnitude of the previous definition.

IV. SUMMARY

Certain of the salient features of radiation quantities and units are presented in the following table:

Associated Features	Quantities		
	Exposure	Absorbed Dose	Dose Equivalent
Radiation types	x- or gamma ray	all ionizing	all ionizing
Media in which effects are measured	air	any	biological system
Effects observed	ionization	energy deposited	biological effect
Units	roentgen	rad	rem

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Basic Principles of Radiation Detection Instruments

I. INTRODUCTION

Since man can neither sense nor measure the presence of radiation, instruments must be used for its detection. Such instruments measure or respond to the charged particles which are produced as radiation interacts with matter. The basic difference between the various instruments is the medium in which the ionizing events occur.

The principal means of detection are: gas ionization, photographic emulsions, scintillation media, semiconductors, chemical decomposition media, radiophotoluminescence and optical density, thermoluminescence, and calorimetry. They will be discussed in the paragraphs that follow.

II. GAS IONIZATION

Radiation detection devices, based on the principle of collecting ions formed by the interaction of ionizing radiation in the chamber wall and enclosed gas, comprise a large segment of all radiation detection instruments now in use. The gases usually used are air or tissue-equivalent gas mixtures, or a mixture of a noble gas and a small amount of a polyatomic gas such as methane or isobutane. The content, concentration, and pressure will vary with the specific function of the instrument.

A. Regions of Response

The relationship of the several types of gas ionization instruments can best be illustrated by a hypothetical experiment which utilizes a detection chamber, a variable voltage supply, and a current indicator of high sensitivity and wide range.

In this experiment, if we expose the detection chamber to a constant source of radiation and apply an increasing voltage across the chamber, the measured current output produced by ionization within the chamber will yield five regions of response, as illustrated in Figure 1.

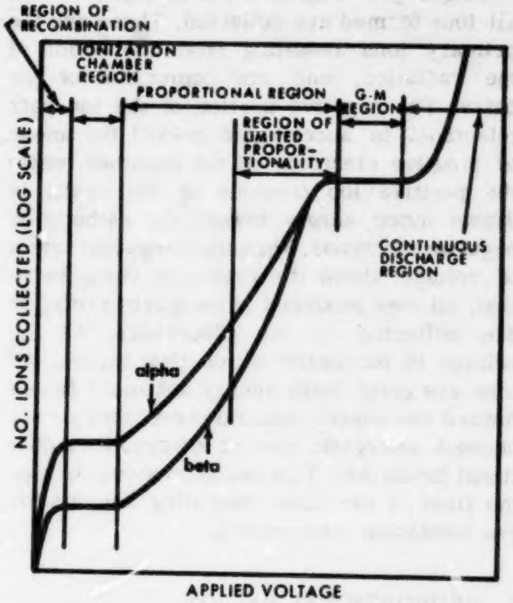

Figure 1.--Regions of Instrument Response

1. RECOMBINATION REGION

In the first region, the ions produced by the radiation will be under very low voltage gradients and will tend to recombine with each other rather than migrate to the electrodes and be collected. This recombination of ion pairs decreases as the applied voltage is increased and finally becomes negligible. At some voltage the field strength will be sufficient to collect essentially all of the ion pairs that are formed. This first region is known as the region of recombination and is usually not useful for the operation of radiation detection instruments.

2. SATURATION OR IONIZATION CHAMBER REGION

This region begins at the voltage at which all ions formed are collected. These are the primary ions resulting from the action of the radiation, and are comprised of ion pairs. The negative portion of the ion pair (electron) is accelerated toward the anode or positive electrode of the chamber, while the positive ion (residue of the atom) is drawn more slowly toward the cathode or negative electrode. For some large increment of voltage above the region of recombination, all ions produced in the gas by radiation are collected by the electrodes. As the voltage is increased within this region, the ions are given more energy and move faster toward the electrodes. However, they do not become energetic enough to produce additional ionization. This second region provides the first of the three operating regions for gas ionization instruments.

3. PROPORTIONAL REGION

If the voltage is increased above the ionization chamber region, the number of ions collected by the electrodes is greater than the number produced by the radiation. Under the voltage gradient, the primary electrons achieve a high enough velocity to cause secondary ionization in the filling gas. This secondary ionization results in an amplification of the number of ion pairs produced by the radiation. Hence, each primary ion pair produces several additional ions which are collected and measured on the instrument.

The number of secondary ions produced for each primary ion pair formed by the radiation is called the "gas amplification factor." As the voltage is raised, the gas amplification factor is increased. Gas amplification factors are normally about 10^3; factors as high as 10^5 or 10^6 are sometimes attained in this region. The number of ions collected is related to the applied voltage, and is proportional to the number of primary ion pairs formed. Thus, an alpha particle with its high specific ionization will produce a much larger pulse of current than will beta radiation with its correspondingly lower energy and lower specific ionization, illustrated by the alpha and beta curves respectively in Figure 1. This fact makes possible pulse height discrimination between alpha and beta which differ in the amount of primary ionization produced.

This proportionality (of the number of ions collected to the primary ionization) is the reason for naming the third region of instrument operation "the proportional region." The upper part of this region, where the two curves begin to approach each other (see Figure 1), is referred to as the "region of limited proportionality" and is not generally used in radiation instrumentation. This limit is controlled by the physical dimensions of the counter and the number of gas atoms present. The true proportional relationship no longer exists in this upper region.

4. GEIGER-MUELLER REGION

In the G-M region the increased voltage accelerates the primary electrons. These latter interact with gas molecules, producing a sequence of ionizing events during their travel to the anode. When the secondary ionization does start, it builds up rapidly, since the secondary ionizing events can also produce more ionization. The buildup of ionization, referred to as a "Townsend avalanche," then collects on the central electrode.

Since a single ionizing event can produce a very large number of ions, the number of ions collected is relatively independent of the applied voltage and the specific ionization of the incident radiation. G-M counters operating in the G-M region provide a gas amplification factor as high as 10^{10} and are extremely sensitive to any radiation which produces even one ion pair. Consequently, individual ionizing events may be detected.

The positive ions (often argon) produced during this avalanche of electrons migrate to the cathode, where their electron deficiency is satisfied by the excess negative charge at the cathode. When the vacant orbits of the gas atoms are filled, electromagnetic radiation is emitted. This radiation, which may be either ultraviolet or x radiation, tends to continue the discharge action, and so sustain the period during which the gas is essentially a conducting medium.

5. CONTINUOUS DISCHARGE REGION

If the voltage is increased above the G-M region the gas arcs, thereby producing a state of continuous discharge.

The experiment described (utilizing a detection chamber, a variable voltage supply, and a current indicator of high sensitivity and wide range) is theoretically possible. But in practice one does not convert an ionization chamber to a proportional counter or G-M counter by merely raising the voltage. For practical reasons these instrument types differ from each other not only in voltage but in configuration and composition of the contained gas.

B. Operational and Practical Considerations

The operational characteristics of detection instruments occur primarily in three of the five regions of instrument response. The first--the ionization chamber region--provides low sensitivity but high range, since it measures only the primary ionization produced. Discrimination between the several types of radiation is not possible except by use of external absorbers. The operating voltage for ionization chamber instruments will usually be between 60 and 600 volts, depending upon the filling gas (usually air at atmospheric pressure) and the physical size and shape of the chamber.

Proportional instruments provide a high sensitivity due to their gas amplification and a (relatively) high range, since the secondary ionization takes place over only a portion of the chamber volume. Due to the proportionality factor which exists in this region, the instrument is inherently capable of discriminating between different types of radiation. Proportional counters are usually filled with a mixture of argon and methane, although air is sometimes used. Operating voltages range from 500 to 5000 volts, depending upon chamber design and filling gas.

The G-M region provides high sensitivity, since any ionizing event occurring within the G-M tube can be counted. It has a low range due to the discharge dead time (the time during which the gas is conducting and therefore insensitive to any further ionizing events). Because of the nature of the discharge, it is impossible to discriminate between the various types of radiation in this region. Geiger-Mueller chambers are usually filled with argon or helium (and in most cases, a quenching vapor) at lower than atmospheric pressure. They operate in the range of 600 to 3000 volts.

To suppress the secondary emission of electrons from the cathode, a quenching agent is used. Organic quenching agents, usually polyatomic molecules such as ethyl alcohol, absorb the energy from the positively charged ion and dissociate into smaller particles which do not emit ultraviolet light and hence cannot eject electrons from the cathode. The useful life of the organically quenched tube is limited by the number of quenching molecules present. Organically quenched tubes have a reasonably flat plateau. The use of halogen gases will produce the same quenching effect; however, the halogen ions apparently recombine after dissociation and therefore do not limit the life of the tube.

The G-M region is illustrated in Figure 2. The threshold voltage is that applied voltage where the pulses are first detected and the avalanche effect results with further voltage increase. Normal operating voltage is selected at approximately one-third the plateau distance to obtain the greatest stability and life of the tube. Sustained operation in the continuous discharge region will result in permanent damage to the G-M tube.

Each of the regions provides certain operating characteristics described above

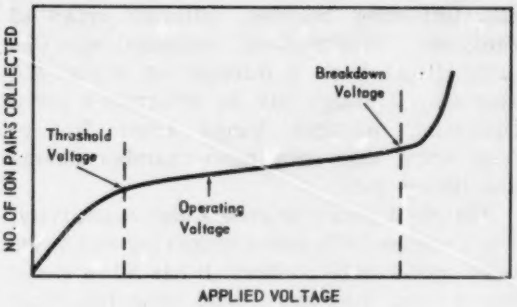

Figure 2.--G-M Response Curve

which makes it useful for one purpose or another: The ionization chamber region, providing a direct indication of the number of ions produced by a given radiation, is eminently suitable for indicating cumulative exposure or radiation exposure rate. Ion chambers are not sensitive to low radiation intensities, but complementary to their low sensitivity is their ability to measure large doses or high radiation intensities. Proportional instruments find their best use in the discrimination between alpha and beta radiation, while G-M instruments are extremely sensitive indicating devices for measuring low intensities of radiation. Both the proportional and the G-M instruments are counters; that is, they provide a pulse of current for every particle or photon which interacts within the chamber. These two types are useful in the measurement of radioactivity.

III. PHOTOGRAPHIC EMULSIONS

The first method used to detect nuclear radiation was the exposure of photographic plates. Becquerel thus discovered radioactivity. Radiation interaction with the silver halide in the photographic emulsion results in ionization. The silver ions produced are attracted to the negatively charged sensitivity center in the crystal, where the silver ions are reduced to free silver. This concentration of silver ions is known as the "latent image" and is proportional to the incident ionizing radiation. The latent image acts as a catalyst during the developing process to convert the grain to free silver. This results in an image amplification factor of approximately 10^{10}. The fixing process dissolves the non-reduced silver halide in the emulsion, leaving the final radiograph.

Photographic emulsions are used extensively in research, autoradiography, quality control, and personnel monitoring.

With the proper selection of film, filters, etc., the film exposure may be related to the type, energy, and quantity of radiation received by the film.

IV. SCINTILLATION MEDIA

Scintillation detectors were in use as early as 1908, and played an important part in the experiments of Rutherford and his collaborators. However, scintillation counting was not widely used until 1947, when the newly developed photomultiplier tube eliminated the tedium of counting scintillations under the microscope. The theory of scintillators is based on the luminescent property of certain materials. The interaction of radiation in a scintillation media results in absorption of energy. This energy raises a molecule or an ion to an excited or elevated energy state. The return to lower energy or metastable state levels, and finally decay to the ground state, results in the emission of energy as visible or near-visible light. The magnitude of each light pulse is proportional to the energy deposited in the medium. The energy deposited in the medium more closely approaches the total energy of the incident radiation as the volume of the scintillating medium increases. The combination of the phototube and suitable electronic circuits has resulted in a very effective counting system.

The sequence of transforming the energy of ionizing radiation into measurable electrical signals is illustrated in Figure 3. The advantages of the scintillation detector are the high efficiency in gamma ray detection compared to gas flow detectors, the capacity

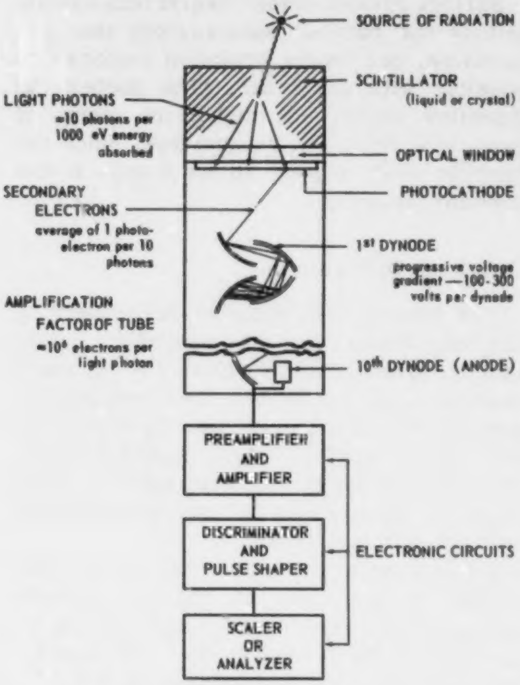
SOURCE OF RADIATION
SCINTILLATOR (liquid or crystal)
LIGHT PHOTONS ≈10 photons per 1000 eV energy absorbed
OPTICAL WINDOW
PHOTOCATHODE
SECONDARY ELECTRONS average of 1 photo-electron per 10 photons
1st DYNODE
progressive voltage gradient —100-300 volts per dynode
AMPLIFICATION FACTOR OF TUBE ≈10⁶ electrons per light photon
10th DYNODE (ANODE)
PREAMPLIFIER AND AMPLIFIER
DISCRIMINATOR AND PULSE SHAPER
SCALER OR ANALYZER
ELECTRONIC CIRCUITS

Figure 3.--Schematic Diagram of Scintillator-Photomultiplier Counting System

to handle high counting rates because of the very short resolving time, and the ability to detect different types and energies of radiation. Perhaps the greatest use of scintillation counters is in measuring the energy spectrum of gamma emitters. Liquid scintillation systems have the advantage of high sensitivity, accuracy, reasonable stability and reproducible geometry. They have the disadvantage of poor resolution. Solid scintillation systems have high sensitivity and high resolution, but reproducible geometry is more difficult to attain.

Some of the most common scintillation media are: silver-activated zinc sulfide for the detection of alpha radiation, anthracene, naphthalene, stilbene, and liquid scintillators such as 2, 5-diphenyloxazole (PPO) and 2, 2-p-phenylenebis (5-phenyloxazole) (POPOP) for measuring beta radiation; and thallium-activated sodium iodide crystals for gamma detection.

V. SEMICONDUCTORS

Semiconductors use a dense ionizing medium, so photons of higher energy can be stopped completely within the medium. The ionizing events produce an electric field at the junction surface of two semiconductor materials. The most widely used types of semiconductor devices are diffused p-n junction, surface barrier, and lithium drift detectors.

A. Diffused p-n Junction

The diffused p-n junction detector obtains its name from its manufacturing process. A slice of p-type silicon or germanium crystal with a layer of n-type impurity (usually phosphorus) deposited on the surface is heated to form a p-n junction just below the surface. The phosphorus may also be painted onto the silicon and made to diffuse into it by applying heat. Since the n-type crystal has an excess of electrons and the p-type has an excess of "holes" (holes may be thought of as unit positive charges), the natural action of the crystal tends to align the electrons on one side of the junction and the holes on the other. Thus, a difference of potential is built up across the junction.

By applying an external voltage to the crystal of such polarity as to oppose the natural movement of electrons and holes (reverse bias) the potential barrier across the junction is increased and a "depletion region" produced. (See Figure 4.) This

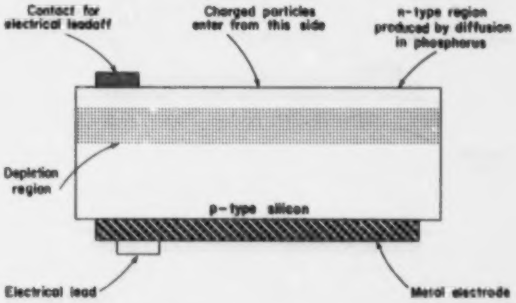
Contact for electrical leadoff
Charged particles enter from this side
n-type region produced by diffusion in phosphorus
Depletion region
p-type silicon
Electrical lead
Metal electrode

Figure 4.--Schematic Representative of a Diffused p-n Junction Detector

depletion region is the sensitive volume of the detector, and is analogous to the gas volume in a gas ionization detector. Charged particles entering the depletion region produce electron-hole pairs analogous to ion pairs produced in gas ionization chambers. Since an electric field exists in this region, the charge produced by the ionizing particle is collected, producing a pulse of current. The size of the pulse is proportional to the energy expended by the particle.

B. Surface Barrier Detectors

The operating principle of the surface barrier and lithium drift detectors is the same as for the p-n junction, in that a depletion region exists when an electric field is produced. The method of producing the depletion region, as well as its dimensions and location within the crystal, vary from one type to another.

The surface barrier detector depends for its operation upon the surface states of the silicon or germanium. At the surface of a piece of pure crystal, an electric field exists such that both holes and electrons are excluded from a thin region near the surface. For n-type crystals, the field is such as to repel the free electrons from this region. If a metal is joined to the crystal the free electrons are still repelled, but a concentration of holes is produced directly under the surface. If a reverse bias is then applied, a depletion region is produced. (See Figure 5.)

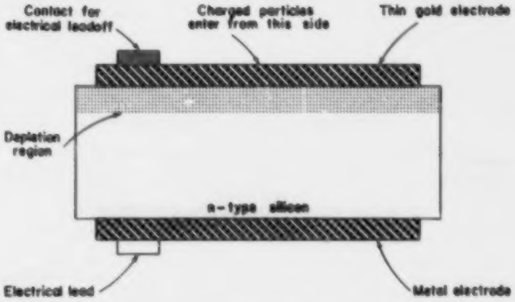

Figure 5.--Schematic Representation of a Surface Barrier Detector

Surface barrier detectors give better resolutions for particle spectroscopy than p-n junctions, but deeper depletion regions are possible with the latter. (The deeper the depletion region, the higher the energy of particles which can be analyzed, since the particle must expend all its energy in the depletion region.)

C. Lithium Drift Detectors

The lithium drift detector is produced by diffusing lithium into low resistivity p-type silicon. When heated to about 150° C under reverse bias, the lithium ions drift into the junction in such a way that the impurities are compensated to form a depletion region of high resistivity intrinsic silicon. Wide depletion regions may be obtained at low bias voltages in this manner.

Semiconductor detectors have been popular mostly in the area of charged particle spectroscopy. Much better resolution can be obtained in these devices than with scintillators or grid-type ionization chambers.

VI. CHEMICAL DECOMPOSITION INDICATORS

Since radiation can cause ionization, it is possible to use the ionization produced in a chemical system as an indication of the amount of radiation received. This is done in the case of chemical decomposition indicators: Ions produced by radiation combine chemically to form new compounds or change chemical characteristics from those existing in the pre-irradiation stage.

A typical chemical decomposition indicator is a chloroform-water mixture. When exposed to radiation, it produces hydrochloric acid in proportion to the radiation absorbed. This formation of acid decreases the pH. By the use of a suitable indicator, it is possible to ascertain when a predetermined dose has been received by the chemical system. An indicator frequently used in this system is bromcresol-purple.

An inherent drawback of chemical decomposition systems is the fact that the sensitivity to radiation is quite low. While these systems require higher exposure rates for detectable chemical change, newer systems are being developed to respond to lower exposures.

VII. RADIOPHOTOLUMINESCENCE AND OPTICAL ABSORPTION

Radiophotoluminescence is the phenomenon by which certain materials undergo changes in their photoluminescent properties after irradiation. Irradiated material will fluoresce when activated by light of the proper wavelength (ultraviolet or near-ultraviolet), while unirradiated glass will not fluoresce under the same conditions.

Silver-activated phosphate glass has proved a useful radiation detecting medium, exhibiting the photoluminescence property. The ionizing radiation liberates electrons within the glass. These are trapped by the Ag^+ ions of the glass. The resulting metallic silver centers serve as the origin of the photoluminescence. After radiation exposure of the glass, it is subjected to ultraviolet light and the resulting fluorescence detected by a photomultiplier tube. The intensity of the light emitted is proportional to the dose. Personnel dosimeters of this type have been developed which cover the range from 10 mR to 10^4 R.

Higher radiation doses may be determined by measuring the increased optical density of the glass after irradiation. This is done by making optical transmission measurements using light of the proper wavelength for the dose range of interest. This principle is useful from 10^3 to 10^6 rads.

VIII. THERMOLUMINESCENCE

Thermoluminescence is the phenomenon whereby certain materials can absorb and store energy from ionizing radiation, and release this energy as light in the visible or near-visible region of the spectrum when the material is heated. Irradiation of a luminescent material results in the excitation of electrons (see Figure 6) from the ground state to the conduction band of the material (a). The electrons are then trapped in a metastable state, present as imperfections in the crystal lattice of the material (b).

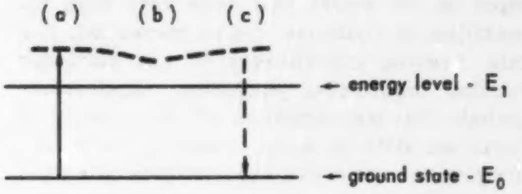

Figure 6.--Schematic of Electron Energy Bands

The electrons stored in the metastable state are activated by the addition of energy in the form of heat. The electron is then able to return to the ground state, and the energy released as light (c). The light intensity is proportional to the energy absorbed in the material from the original ionizing radiation. The TLD (thermoluminescent dosimetry) system requires a separate readout system which can measure either the integrated light output during, or the peak light output after, a constant heating cycle.

TLD is most widely used in personnel dosimetry and special research projects.

IX. CALORIMETRY

Calorimeters take advantage of radiation's heating effect to detect its presence. A calorimeter is a device for the measurement of quantities of heat. Calorimeters have received greatest application in the determination of the radiation-energy absorption in material, since ultimately the absorbed energy is degraded into heat. Calorimetry can also be used to determine the activity of a sample of radioactive material. The main advantage of the calorimetric method for measuring absorbed energy or activity is its inherent accuracy. For dosimetry purposes a direct reading of energy absorption can be obtained. However, the rate of heat input is so small that only very high intensities of radiation can be measured. For this reason, calorimetry is not used for routine monitoring purposes. Applications include the measurement of the activity of curie amounts of alpha emitters, the measurement of the energy of particles produced by particle accelerators, the dose from high intensity x-ray machines, etc. Calorimetry provides the only fundamental method for measuring absorbed dose.

X. SUMMARY

Radiation detection instrument design has been dictated by the exposure rate or activity to be measured, the type and energy of the radiation, accuracy desired, and the area of interest in which the data are to be used. Each of the primary means of detection discussed has inherent advantages and disadvantages. Laboratory and research studies should utilize all types of media for specific applications. Survey instruments use predominately gas ionization and scintillation media. Personnel monitoring instruments rely on gas ionization, photographic emulsions, and thermoluminescent media for detection of radiation.

As a result of these considerations, radiation detection instruments may be divided into three groups:

1. Personnel monitoring instruments, which measure accumulated exposure that can be related to the dose equivalent.
2. Survey instruments designed to measure exposure rate in milliroentgens per hour (mR/hr) or activity in counts per minute (cpm).
3. Laboratory instruments designed primarily to relate the ionizing events in terms of units of activity (curie).

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Survey Instruments

I. INTRODUCTION

None of the ionizing radiations is detectable by any of man's five senses, therefore all indications of their presence and intensity must be obtained by instruments. Radiation detection devices, like other measuring instruments, operate because of some effect the phenomenon being measured has on matter. In the case of radiation, this effect is ionization. Survey meters are similar to other radiation detection instruments in their operational characteristics. A good survey meter should be portable, rugged, sensitive, simple in construction, and reliable. Portability implies lightness and compactness with a suitable handle or strap for carrying. Ruggedness requires that an instrument be capable of withstanding mild shock without damage. Sensitivity demands an instrument which will respond to the type and energy of radiation being measured. Rarely does one find an instrument capable of measuring all types and energies of radiation that are encountered in practice. Simplicity in construction necessitates convenient arrangement of components and simple circuitry comprised of parts which may be replaced easily. Reliability is that attribute which implies ability to duplicate response under similar circumstances. All these conditions are not met in any one instrument, but they are approached in many. In any monitoring operation, one must select the proper instrument, use it intelligently, and then be able to interpret the results of the meter readings.

II. IONIZATION CHAMBERS

A. Theory

Ionization chambers are instruments in which the ionization initially produced within the chamber by radiation is measured without further gas-amplification. Primary ions formed in the chamber are attracted to the respective electrodes, and the current pulses are amplified externally to a measurable current. The gas-amplification factor is thus one.

B. Physical Description

Ionization chamber survey meters have three principal components: (1) the ionization chamber; (2) the electronic circuit; and (3) the dial or indicating meter.

(1) Ionization Chambers are usually about 30 to 50 cu. in. in volume and are filled with air at atmospheric pressure. The chamber wall design and type of material used in its construction determine the types of radiation to which it is sensitive. The larger the chamber the more sensitive the instrument and the greater the voltage required for proper operation. Practically all chambers have walls that conduct electricity and serve as the cathode, while wires mounted in the center of the chambers constitute the anode. Operating voltage is supplied by batteries and has a magnitude of about 100 volts. The current which flows is directly related to the type, energy, and quantity of radiation penetrating the chamber. With movable shields, as in the "Juno," it is possible to discriminate between types of

radiation. In general, ionization chamber survey meters are used to measure relatively high level intensities. Their low sensitivity enhances their capacity to measure radiation at higher dosages or exposure rates.

(2) The electronic circuit is actually a precision amplifier. Vacuum tube or transistor circuits are used to build up the feeble ionization current so that it may be measured directly by a microammeter. Most survey meters incorporate a system whereby the amplification characteristics of the circuit may be changed by factors of ten. This enables the operator to change the instruments' range and sensitivity.

Since there is a gas amplification factor of unity, circuit amplification becomes a problem which one does not necessarily have in a GM instrument. On the other hand, there is no problem of quenching the discharge or of losses due to coincidence.

(3) The indicating meter is usually a microammeter that registers the amplified current. The dial is generally calibrated in milliroentgens/hour or, in the case of contamination monitors such as the "Samson," in counts per minute.

C. Operation

Most ionization chamber survey instruments have a selector switch marked "off," "wait," and x1, x10, x100. When the switch is off, the batteries are disconnected and the meter is short-circuited making the instrument inoperative. With the switch in the wait position, the batteries are connected, permitting the circuit to warm up and the instrument to be zeroed after a warmup period of from 1 - 5 minutes. The meter is connected while the ionization chamber is disconnected making it possible to adjust the meter accurately to zero even in the presence of radiation.

The ionization chamber does not wear out or suffer changes in characteristics as GM tubes do; however, the circuit of the ionization chamber survey meter has more elements that can get out of adjustment if not properly handled. Loose leads and weak batteries are a source of trouble which can be readily serviced. Other difficulties are usually caused by faulty circuits which cannot generally be fixed without the aid of a competent service man.

No aural indication is used in IC instruments and thus the operator must constantly watch the meter to ascertain the field intensity. There is a lag between the instant radiation enters the chamber and the time when the meter reaches its maximum reading; therefore, one must allow time for the meter to reach its maximum before taking a reading. This is on the order of a few seconds.

D. Calibration

Instruments are designed by manufacturers to read directly in radiation intensity units, generally mr/hr or r/hr; however, there is considerable error in a direct reading, since the characteristics of individual components causes variations in instrument response. Each instrument must be calibrated for accurate interpretation. Instrument response intended by the manufacturer is related to one type of radiation, usually of a definite energy range. If radiation of a different energy or type is measured, the results will be incorrect and the instrument must be recalibrated with radiation of the same type and energy that is to be measured.

For gamma ray calibration an ionization chamber instrument can be checked by placing it in a known field of radiation. Radium and Co^{60} are the most frequently used sources for gamma calibration. A plot of scale readings versus true radiation intensity can be made by comparing scale readings at known distances from the source against the true intensities at these distances, employing the formulae given below.

$$I = \frac{\text{milligrams of Ra}}{D^2}, \text{ or } I = \frac{1.59 \times \text{millicuries of Co}^{60}}{D^2}$$

where: I = Intensity, mr/hr

D = Distance from source to detector, yards

From five to ten equally spaced scale readings should be taken and a graph of these values versus the calculated intensities at the corresponding points should be plotted on linear graph paper. A typical calibration curve would plot meter readings on the ordinate and corresponding "true" intensities on the abscissa.

When calibrating an instrument, the reference point of the instrument is generally considered as the center of the sensitive volume. It should be pointed out that the ionization chamber type survey instrument, when properly calibrated, will give a good measurement of x- or gamma radiation intensity, but for alpha and beta radiation, only qualitative measurements can be made.

E. Uses

In x-ray survey work, calibrated ionization chamber instruments are very useful for measuring dose rate. Ion chambers are used extensively for beta and gamma survey work, and if properly modified, they may be used for neutron monitoring.

F. Typical Instruments

Cutie Pie: Perhaps the most widely used and one of the most versatile ionization chamber instruments available for radiological survey work is the Cutie Pie. These are available with maximum scale readings up to 50 roentgens/hour.

Condenser r-meters: A very reliable and accurate instrument for x-ray calibration is the condenser r-meter. By nature, the condenser r-meter measures cumulative dose. It consists of a charger-reader mechanism and several detachable ion-chambers. These chambers are charged and then left in a radiation field for a known time. When read on the charger-reader, they show the total dose received during the time of exposure. Ionization chambers for condenser r-meters are available in ranges from 0.025 roentgens full scale to 250 roentgens full scale and are nearly energy independent (- 2%) for x-ray energies of 30 Kev effective to 400 Kev effective.

III. GEIGER-MUELLER INSTRUMENTS

A. Theory

Essentially, the theory of ion collection in the GM type detector is the same as for the IC instrument except that there is the formation of secondary electrons; that is, primary ions, formed by the incident radiations, are accelerated (given energy) by the high voltage potential and this added energy enables them to produce secondary ion-pairs. The ratio of the total number of secondary ion-pairs produced to the primary ion-pair (Gas Amplification Factor) may be as high as 10^9. For control of the amplification, a quenching gas is introduced. The avalanche, caused by radiation entering the Geiger-Mueller tube, sends a pulse to the indicating unit of the survey instrument. The quenching gas functions to stop the avalanche and makes the GM tube ready for another ionization event. The amplification, inherent in the detector tube, allows a single beta particle or gamma photon to be detected.

B. Physical Description

The principal elements of the portable Geiger counter are: (1) the GM tube with its housing; (2) the electronic circuit; and (3) the meter.

(1) The GM Tube is essentially a glass tube filled with an inert gas at less than atmospheric pressure. The filling gas, usually argon, yields ion pairs (when irradiated). Generally, the tube wall is the cathode and the wire traversing the axis of the tube is the anode. Some tubes have a thin window which admits alpha particles, but these are not used in survey meters to any extent.

Each GM tube has its own characteristic curve of counts/minute versus voltage, which will vary with usage of the tube. The operating voltage must be well up on the Geiger plateau for the proper operation, and it is generally in the range of 1 to 2 thousand volts.

To count efficiently, Geiger tubes must have adequate means for quenching the ionization avalanche started by a particle entering the tube. In survey Geiger counters the tubes are invariably self-quenching; that is, the gas within the tube contains from 10 to 25 per cent vapor of a substance such as ethylene or iso-butane. Quenching gas is decomposed by radiation, therefore a self-quenching tube has a limited lifetime. It is thus obvious, that a Geiger counter should not be left turned on when not in use, especially near a source of radiation.

With a self-quenching tube there is a brief lapse of time from the moment one particle enters the tube until the tube is ready to count the pulse produced by another particle. The initial ionization, the avalanche, the registration of the pulse, and the quenching, all take place in the matter of a few microseconds; then the tube must be cleared in the residual ions. This clearing requires a few hundred microseconds. Dead time becomes important when measuring intense radiation fields.

Most Geiger tube walls are designed so that all but the weakest beta particles may enter. Allowing for the errors due to simultaneous entry, each and every beta particle entering the tube will be counted. Gamma ray counting is not nearly so efficient.

Since one measures each beta particle and each gamma ray that produces ionization within the sensitive tube volume, the instrument is extremely sensitive to radiation, and on the most sensitive scales background levels can be read.

A discriminating shield is provided for the GM tube or probe which when open admits both beta and gamma. With the shield closed only gamma is admitted.

(2) The Electronic Circuit provides the desired voltage to the GM tube, assists in quenching the discharge and receives, amplifies and transforms pulses from the tube to the type of impulse that can be heard in an earphone and registered on a microammeter.

(3) The Indicating Mechanism on most Geiger counters is usually twofold; that is, earphones for aural indication and a meter for visual indication. The meters are in reality microammeters that indicate radiation intensity by a pointer on a scale. The pointer or needle will waver slightly and an average reading should be used. In general, the dial is calibrated either in counts/minute or in milliroentgens/hour, or both. Also, the instrument has a switch for selecting different ranges of sensitivity. For the mr/hr scale, the sensitivities are usually indexed indicating full scale values at a particular switch position, whereas the counts/minute scale is usually marked by x1, x10, x100, or x1,000 of full scale as read on the face of the dial.

Equipment failure is generally due to batteries (some instruments have a battery check in the "on" position), loose connections or faulty GM tube.

C. Operation

The operation of the GM Survey Instrument is essentially the same as that of the IC Survey Instrument. The warmup period is much less critical, and usually 5 to 10 seconds is ample. Care should be taken not to exceed the maximum capacity of the instrument; such excessive exposure will likely damage the GM detecting tube. The GM tube is in operation when in the "on" position and no zero adjustment is possible. It is important to remember that GM survey meters are sensitive instruments and in general do not read high levels of radiation intensity.

D. Calibration

The calibration of GM instruments is the same as for the IC type. The only change that might be noted is that a smaller source of radiation might be used for calibration, since the sensitivity of the GM is much greater than that of the IC instrument.

E. Uses

Survey Geiger-Mueller instruments are useful for low level beta, and gamma ray survey work; with proper modification, they may also be used to monitor for neutrons. Portable GM instruments are available in a variety of types and full scale ranges from .2 mr/hr to 50 mr/hr.

IV. PROPORTIONAL SURVEY INSTRUMENTS

A. Theory

This type instrument derives its name from the fact that it operates in the proportional region of the typical instrument response curve. The probe has an extremely thin window which admits alpha particles to the ionization chamber. The operating voltage is quite high, in the order of 1,500 to 4,000 volts. Gas amplification factors are in the order of 10^5 to 10^6. This instrument can be made to respond only to alpha particles, by choosing the proper operating point in the proportional region, and by circuit adjustment. Alpha particles, since they have the highest specific ionization, give greater pulses than do beta and gamma; thus, by properly adjusting the input sensitivity of the main instrument circuit, we can eliminate all indications from the detecting element except those produced by alpha particles.

B. Physical Description

Proportional survey instruments have three principal components: (1) the ionization chamber; (2) the electronic circuit; (3) the meter.

(1) The Ionization Chamber has walls which serve as one electrode, and wires transversing the chamber which function as the opposite electrode. Such a chamber contains air or gas at normal pressure. A thin window of nylon, etc., allows alpha particles to enter, and the ionization they produce causes secondary ionization proportional to the production of primary ion pairs.

(2) The Electronic Circuit is more complex than that used in other type instruments. It is necessary to control the chamber voltage within fairly narrow limits.

(3) The Meter is marked in counts/minute with several sensitivity scales. The dial is used in a manner already discussed.

C. Operation

The operation of the proportional radiation survey instrument is similar to other instruments. A warmup period of several minutes is usually required to allow the circuit to become properly energized.

D. Calibration

Calibration of proportional meters for alpha contamination is accomplished by means of known quantities of the alpha emitter in question deposited on planchets.

E. Uses

Proportional survey instruments find their greatest application in alpha survey work. In making any alpha survey, the instrument probe must be extremely close to the surface being monitored.

V. SCINTILLATION SURVEY INSTRUMENTS

A. Theory

Scintillation counters depend upon the light produced when ionizing radiation interacts with a phosphor or crystal of certain substances capable of producing this light. The scintillations produced in the phosphor or crystal are then permitted to fall on a photomultiplier tube which converts the light pulses to electrical impulses. These electrical impulses may then be amplified and caused to register on a microammeter.

B. Physical Description

Scintillation type survey instruments have four principal components: (1) the scintillating phosphor or crystal; (2) the photomultiplier tube; (3) the electronic circuit; and (4) the meter.

(1) Scintillating Phosphors may be liquid or crystalline, but for survey work, the crystalline type is, at present, preferable. If one is interested in detecting alpha radiation, a silver activated zinc sulfide screen (similar to the sensitive screen of a television picture tube) is generally used.

For the detection of beta radiation, an anthracene crystal, covered with a thin metal foil to shield out alpha radiation, is preferable; for x- or gamma radiation a sodium iodide crystal is generally employed. When it is desirable to detect neutrons, a secondary reaction must be employed such as the reaction of thermal neutrons with boron in which an alpha particle is released. The alpha particle may then be detected with a ZnS phosphor.

(2) The Photomultiplier Tube picks up light flashes from the phosphor which is in contact with it, and converts these light flashes to electrical impulses. It consists of a photosensitive screen, which emits electrons when light falls on it, and a series of dynodes at a positive potential with respect to the photocathode and with respect to each other. An electron liberated in the photocathode is accelerated to the first dynode, which is about 100 volts positive to the photocathode, where it knocks out additional electrons that are accelerated toward the second dynode. The second dynode is 90 to 100 volts positive to the first dynode and the electrons striking the second dynode produce still more electrons. This multiplication process proceeds through each successive dynode until the electrons reach the anode. From this process, the current amplification is in the neighborhood of 10^9 - 10^{10}.

(3) The Electronic Circuit serves to maintain the voltage across the elements of the photomultiplier tube and to amplify the current impulses from the photomultiplier tube to a magnitude great enough to read on a meter.

C. Operation

Operation of scintillation survey instruments is similar to that of ion chambers and GM instruments. It should be pointed out that the photomultiplier tube of a scintillation instrument will be ruined if exposed to light without first removing the voltage applied to the tube.

D. Calibration

Scintillation instruments may be calibrated in the same manner as is used for a GM or an ion chamber instrument.

E. Uses

As previously pointed out, scintillation devices may be used to detect either alpha, beta, gamma, or x-rays or neutrons simply by placing the proper phosphor in contact with the photomultiplier tube. Scintillation detectors are very sensitive, more sensitive and efficient than GM counters, particularly to gamma radiation. They may be used to detect extremely low levels of activity, as the noise background may be kept much lower than that encountered in the circuiting of a GM or ion chamber instrument. Losses due to dead time in a scintillator are very slight, as light flashes may be produced in many portions of the phosphor at the same time, and the decay time of these flashes is very short; consequently, scintillators are useful for measuring very high radiation intensities.

Personnel Instruments

I. INTRODUCTION

A. It is extremely difficult to measure the absorbed dose or energy deposition in tissues from varieties of radiations. The conditions under which one must work are generally complex, ill defined and irregular. Normally, the best one can hope for is an estimate of the exposure dose to x and γ radiation. To do this requires, usually, not one instrument or method but several. Perhaps the most practical, although less accurate, is the film dosimeter. With adequate definition of radiation conditions and proper control and interpretations, it is possible to evaluate radiation exposures under which personnel must work. This usually gives one enough material from which the absorbed dose might be inferred. Then if such inferences are further substantiated with dosimeter or pocket chamber data and dose rate information from survey instruments one could finally arrive at a rather reliable dose estimate. Therefore the devices of most general importance and which will be discussed below are: (1) film badges, (2) pocket dosimeter, and (3) pocket chambers. Survey meters are covered elsewhere in this manual. Due to the increasing interest in chemical dosimeters, rather than their importance as a personnel monitoring instrument, certain fundamental properties of this device are also mentioned.

II. FILM DOSIMETRY

A. Emulsion

There are a variety of different types of emulsions but the feature in common is a gelatin base with silver halide which is spread on film (cellulose) or glass. The thickness ranges from a few microns to several hundred microns. The most common thickness for nuclear emulsions is from 10 to 25 microns. This corresponds to a mass of about 2 to 5 mg/cm^2. Over the emulsion there is usually a thin protective coating of gelatin sometimes referred to as a T coat (about 0.5 microns). The silver halide grains in most emulsions are silver bromide. The grain size is quite important in determining sensitivity. Of course other constituents of the emulsion as well as developing techniques may modify sensitivity. The constituents or type of the emulsion may be varied depending on the type radiation and the levels to be encountered. For example, if one is concerned with recording the tracks of heavy particles, the grain abundance is adjusted to about 3 times that used in ordinary optical emulsions. Also, certain sensitizers may be added, for example, Boron-10, to greatly increase the sensitivity for thermal neutrons.

B. Theory of Latent Image Formation

The radiation loses energy by setting free or raising the energy of one or more electrons into the conduction energy band of the crystal. Probably more than one ionization event is required. The electrons migrate about the crystal, eventually being trapped in "sensitivity centers" which might consist of impurities or deformities in the crystal lattice. The electrostatic potential set up about the centers results in the accumulation of some silver ions which tend to move freely in the crystal. The number of ions which take part in such migration depends primarily on the temperature. These ions collect around the sensitivity centers due to the attraction for the negative electrons. Ultimately, the ions are neutralized to form the silver atoms. These atoms constitute the latent image of the emulsion and act as a catalyst during the development process to completely convert the grain to silver. Thus, the development process is merely an amplification (of about 10^{12}) of what has already transpired. The probability of a latent image being established increases with an increase in the number of electrons in the sensitivity centers; and this number is proportional to the energy absorbed by the emulsion from the radiation.

C. Limitations

1. ENERGY DEPENDENCE

Figure 1 demonstrates the sensitivity of Ilford Line film to x-rays as a function of their effective energy. The gradual rise in sensitivity as the energy decreases is due primarily to the photoelectric interaction with silver at the lower energies. The decrease in sensitivity below 50 Kev is due to absorption within the outer film covering. Although not shown in Figure 1, the sensitivity would tend to decrease slowly as the energy of the photons is increased above 1 Mev. If the film is used to measure dose from photons of known energy and is calibrated for this energy, the measurements would be reliable. On the other hand, if a wide range of energies are to be encountered, the energy dependence should be reduced such that the response is essentially flat from above 50 Kev to 3 Mev (energies outside of these limits should not be measured in units of roentgens[1]). There are several methods which have been used to reduce the energy dependence. A lower silver bromide content would be of some value but this may affect resolution as well as sensitivity.

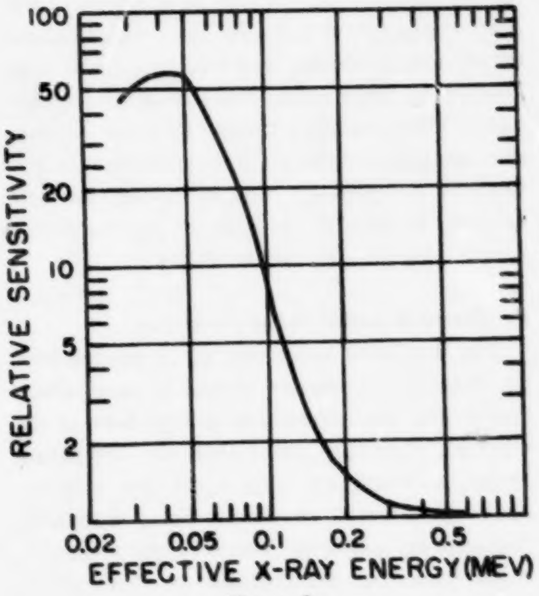


Figure 1

(Reprinted from Hine and Brownell)

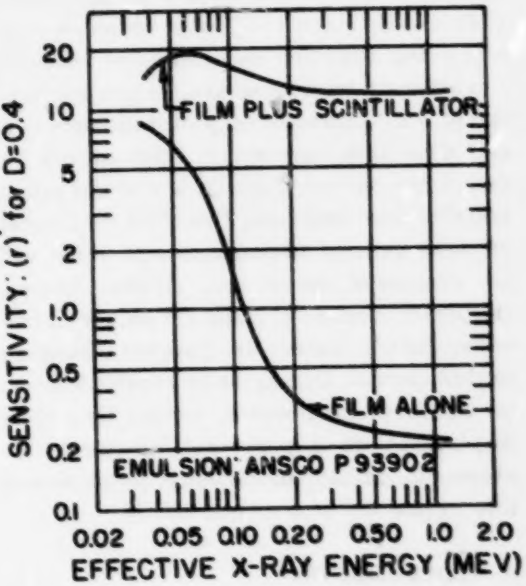


Figure 2

(Reprinted from Hine and Brownell)

Organic scintillators have been used with some success.[2]

The ultra violet fluorescence effectively increases sensitivity as well as improves the energy response. The most common approach has been to utilize a system of filters calibrated to yield information as to the energy of the unknown photons.[3] Such information may then permit an evaluation of the exposure dose.

2. ANGULAR DEPENDENCE

Actually, the dose to material (tissue or emulsion) is independent of the angle of incidence since dose is computed first to an infinitesimal slab then integrated over the entire volume. But film darkening is dependent on angle of incidence. Table 1 illustrates this dependence.

Table 1. Relative Film Badge Sensitivity for γ-Rays Incident at Various Angles

Angle of Incidence	0.11 Mev	0.20 Mev	1.2 Mev
0° (perpendicular incidence)	1.00	1.00	1.00
22.5°	0.87	0.92	0.97
45°	0.46	0.73	0.91
67.5°	0.33	0.45	0.92
90°	0.16	0.41	0.94

3. RATE OF EXPOSURE

The bulk of evidence indicates that the photographic effect is independent of the rate at which that exposure is produced. It is certainly true for intensity ratios of at least 1 to 10,000. There is little knowledge of the effect of microsecond exposures but due to the phenomenon of multi hits (one grain hit by more than 1 particle), it is probably of some significance. On exposures of several days, there is some fading of the film. The fading is influenced by both temperature and humidity. By selection of films of different sensitivity, film dosimeters of wide ranges can be devised. For example, DuPont 502 film can be used from 100 mr to 10 r, while Eastman 548-0 double coat is suitable from 500 to 10,000 r.

4. DEVELOPING TECHNIQUES

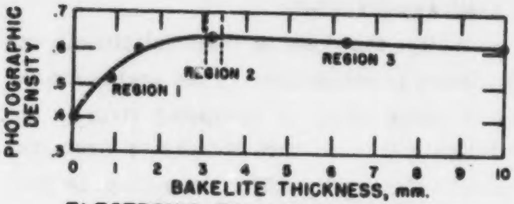
Even slight deviations in the developing time, type, quality and temperature of developer may affect the density in film dosimetry. Therefore, the usual procedure is to develop a set of known standards with each batch of unknown films.

5. MATERIAL SURROUNDING FILM PACKET

Normally, tissue equivalent or air equivalent material is used (lucite, bakelite) having an open window for the detection of beta particles. The thickness of the material must be sufficient to permit electronic equilibrium for the particular energy to be measured. Obviously, in a mixed radiation field, this ideal is difficult and sometimes impossible to achieve. This effect is demonstrated in Figure 3 where the equilibrium thickness is indicated by the dotted line.

D. Neutron Film Dosimetry

1. The measurement of thermal neutron dosage may be accomplished through the



ELECTRONIC EQUILIBRIUM IN BAKELITE, OBTAINED WITH CO^{60} RADIATION

Figure 3

comparison of film densities under cadmium and brass filters. These two filters are designed to attenuate gamma radiation by the same amount. However, because of the (n, γ) reaction induced in the cadmium by the thermal neutrons, the exposure behind the brass when thermal neutrons are present is lower than behind the cadmium. If a wide spectrum of gamma energies are present, a modification of this approach could be used. As an alternative method of measuring neutron dosage, track plates may be used. The fast neutrons interact by (n, p) reactions and the proton recoil tracks are counted and their range is measured. The thermal neutrons interact with the emulsion by N^{14} (n, p) C^{14}; a cadmium filter is usually employed to distinguish between the slow and fast neutrons. The sensitivity for slow neutrons may be increased by adding B^{10} to the emulsion since boron has a very high absorption cross section for thermal neutrons.

III. CHEMICAL DOSIMETRY

Due to the increased use of kilocurie strength sources, there is a growing need for higher range dosimeters. A considerable amount of research is presently underway in this field in an attempt to develop both solid and liquid dosimeters which by color change, photoluminescence, or other alteration, the radiation dose may be estimated.

The principle of such dosimetry is based on the Bragg-Gray Theory which states that the energy absorbed for unit mass of a substance (dE/dm) is related to the degree of ionization (J_m) per unit mass produced in a small air cavity within the material.

$$\frac{dE}{dm} = (W)\ (s_m)\ (J_m)$$

W is the energy absorbed per ion pair in the gas; s_m is the relative mass stopping power in the material to that in the gas. If this principle is used to calibrate the material to be used for a dosimeter, a very high degree of accuracy is possible for a variety of different types of dosimeters.

The effect produced in most liquid dosimeters is due primarily to the radiation effect in water. The primary phenomenon in the irradiation of water is the formation of the free radicals H and OH. These may react to form the products, hydrogen, H_2 and hydrogen peroxide, H_2O_2, as well as to re-combine to form water. Hydrogen may then act as a reducing agent on any chemical present capable of being reduced; and H_2O_2 may act as an oxidizing agent on any chemical capable of being oxidized. One of the more useful chemical dosimeters consists of a mixture of water and a chlorinated hydrocarbon such as chloroform, trichloroethylene, or tetrachloroethylene. In such indicators, hydrochloric acid is produced which may be indicated by means of organic dyes which change color depending on the hydrogen ion concentration.

Silver activated phosphate glass is a particularly useful material for a solid chemical dosimeter. The primary phenomenon of radiation interaction is through a process of radiophotoluminescence. As a result of ionizing radiation, new stable photoluminescent centers are created in certain materials. After irradiation, the materials will fluoresce under light of the proper wave length (usually in the ultra-violet), while unirradiated glass will not fluoresce under the same conditions.

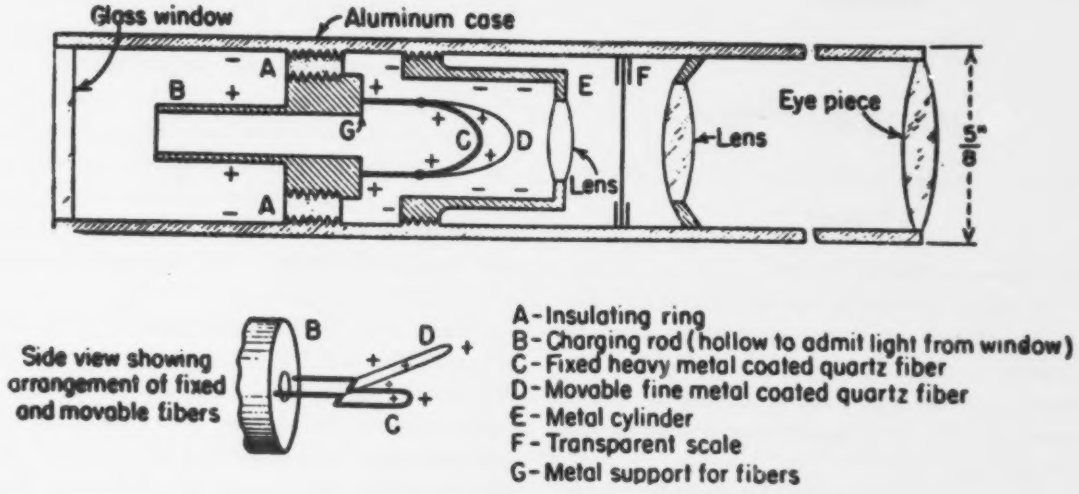
As a final point which should be emphasized, at the present time chemical dosimeters are not very useful in the dose ranges of interest in personnel monitoring. Most chemical dosimeters do not measure exposure doses below about 10 r.

IV. DOSIMETERS AND POCKET CHAMBERS

A. Dosimeters

A pocket dosimeter (Fig. 4) is a chamber containing two electrodes, one of which is quartz fiber loop free to move with respect to its mounting. Like charges are placed on the loop and its moutning, which forces the loop outward from the mount due to the repulsion of like charges. Ionization in the chamber reduces the charge and allows the fiber to move toward its normal position.

An optical system and a transparent scale are all enclosed in the instrument which is about the size and shape of a large fountain pen. The fiber is fused to a metal frame and the microscope is focused on a portion of this fiber. Radiation entering the chamber causes ionization within the sensitive volume. This ionization discharges the electroscope; the distance the fiber moves being proportional to the dose received in the chamber. Instruments of this type can be made sufficiently rugged to withstand the shocks of normal human activity, are small enough to be worn comfortably, and are very useful for measuring integrated exposures. Dosimeters usually are made to have a full scale deflection corresponding to 200 mr, but can also be made with other sensitivities such as 100 mr, 1 r, 10 r, 100 r, etc. The great advantage of this type of instrument is that it can be read at any time without the aid of a supplementary charger-reader by simply holding it up to a source of light and looking into it.


Glass window
Aluminum case
A
B
G
C
D
E
F
Lens
Lens
Eye piece
5"/8
Side view showing arrangement of fixed and movable fibers
A-Insulating ring
B-Charging rod (hollow to admit light from window)
C-Fixed heavy metal coated quartz fiber
D-Movable fine metal coated quartz fiber
E-Metal cylinder
F-Transparent scale
G-Metal support for fibers

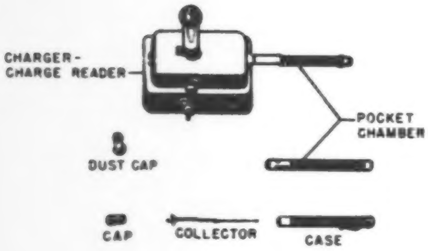
Pocket-dosimeter electroscope.

Figure 4

Reprinted from Ralph E. Lapp and Howard L. Andrews, "Nuclear Radiation Physics", p 199, Prentice-Hall, Inc., 1948.

B. Pocket Chamber

A pocket chamber (Figure 5) has a cylindrical electrode with a coaxial collecting rod well insulated from the rest of the instrument. A charge is placed on this rod. Ions formed in the chamber collect on the rod and reduce the previously placed charge. A pocket chamber differs from the dosimeter mainly in that the electroscope portion (the quartz fiber mechanism and optical system) is in an external unit. This means that the chamber must be charged and read with a separate unit called a "charger-reader". The pocket chamber is similar in size and shape to a fountain pen. The change in charge is measured on a scale that may be calibrated in milli-roentgens. The advantage of this unit is its low cost when compared to a self-reading dosimeter.



POCKET CHAMBER AND CHARGER-CHARGE READER

Figure 5

C. Operation Characteristics

A small amount of dust or lint on an insulator of one of these instruments can be enough to discharge it completely. Therefore, they must be kept clean. Dropping or sudden jarring will also sometimes discharge the instrument.

Insulator "soak-in" is a phenomenon regularly encountered in the operation of these chambers. When an instrument has been out of use for some time and is charged, a rather rapid discharge may be noted. This is due to the penetration of part of the charge into the insulator. It is not leakage in the ordinary sense because it practically disappears if the instrument is kept charged for a day or so. To eliminate this, the instrument should be charged a day or more before it is used. Generally these instruments are designed to respond to x- or gamma radiation, as the walls are too thick to admit beta or alpha radiation.

The chambers are calibrated by the manufacturer to read exposure in milli-roentgens, or roentgens, but they show some energy dependence in their sensitivity and may, therefore, read erroneously. They are relatively energy independent at high energies (greater than 200 Kev) but it is best to know what energy radiation is involved for correct interpretation. Calibration curves can and often should be made for pencil chambers.

V. SUMMARY

Film badges, dosimeters, and pocket chambers are the principal personnel monitoring instruments. Each has specific advantages. Film badges provide a permanent record of exposure, but require more work to obtain readings than the ionization instruments. Dosimeters are especially useful to determine exposure at any time while continuing to act as a monitor without further attention. Pocket chambers are quite simple and therefore represent an inexpensive means of measuring exposure.

There are other personnel monitoring instruments which have limited usefulness in this field. Hand and foot counters are only applicable in permanent locations such as laboratories. Pocket alarms are impractical due to their size and weight, when carried on the person. At the present time, chemical dosimeters are too insensitive for measuring low-level, chronic type of personnel exposures; however they offer a valuable adjunct in estimating dose intensities during radiation accidents and of course there are a variety of research and industrial applications.

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PRELIMINARY DRAFT

Biological Effects of Ionizing Radiation

I. Introduction

The fact that ionizing radiation produces biological damage has been known for many years. The first case of human injury was reported in the literature just a few months following Roentgen's original paper in 1895 announcing the discovery of X-rays. As early as 1902, the first case of X-ray induced cancer was reported in the literature.

Early human evidence for harmful effects as a result of exposure to radiation in large amounts existed in the 1920's and 30's, based upon the experience of early radiologists, miners exposed to airborne radioactivity underground, persons working in the radium industry, and other special occupational groups. The long term biological significance of smaller, chronic doses of radiation, however, was not widely appreciated until relatively recently, and most of our current knowledge of the biological effects of radiation has been accumulated since World War II.

II. Sequential Pattern of Biological Effects

In general, the sequence of events following radiation exposure may be classified as follows:

A. Latent Period

Following the initial radiation event, and often before the first detectable effect occurs, there is a time lag referred to as the latent period. There is a vast time range possible in the latent period. In fact, the biological effects of radiation are arbitrarily divided into short-term and long-term effects on this basis. Those effects which appear within a matter of minutes, days, or weeks are called short-term effects and those which appear years, decades, and sometimes generations later are called long-term effects.

B. Period of Demonstrable Effects on Cells and Tissues

During or immediately following the latent period, certain discrete effects can be observed.

One of the phenomena that is seen most frequently in growing tissues exposed to radiation is the cessation of mitosis or cell division. This may be temporary or permanent, depending upon the radiation dosage. Other effects observed are chromosome breaks, clumping of chromatin, formation of giant

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cells or other abnormal mitoses, increased granularity of cytoplasm, changes in staining characteristics, changes in motility or ciliary activity, cytolysis, vacuolization, altered viscosity of protoplasm, and altered permeability of the cell wall.

It should be pointed out that many of these effects can be duplicated individually with other types of stimuli. However, the entire gamut of effects cannot be reproduced by any single chemical agent. (It is interesting to note that a group of chemical agents that come close to duplicating radiation effects are the nitrogen mustards.)

C. Recovery Period

Following exposure to radiation, recovery can and does take place to a certain extent. This is particularly manifest in the case of the short-term effects, i.e., those appearing within a matter of days or weeks after exposure. There is, however, a residual damage from which no recovery occurs, and it is this irreparable injury which can give rise to later long-term effects.

III. Determinants of Biological Effects

A. The Dose-Response Curve

For any biologically harmful agent, it is useful to correlate the dosage administered with the response or damage produced. "Amount of damage" in the case of radiation might be the frequency of a given abnormality in the cells of an irradiated animal, or the incidence of some chronic disease in an irradiated human population. In plotting these two variables, a dose-response curve is produced. With radiation, an important question has been the nature and shape of this curve. Two possibilities are illustrated in figures 1 and 2.

Figure 1 is a typical "threshold" curve. The point at which the curve intersects the abscissa is the threshold dose, i.e., the dose below which there is no response. If a short-term and easily observable radiation effect, such as reddening of the skin, is taken as "response," then this type of curve is applicable. The first evidence of the effect does not occur until a certain minimum dose is reached.

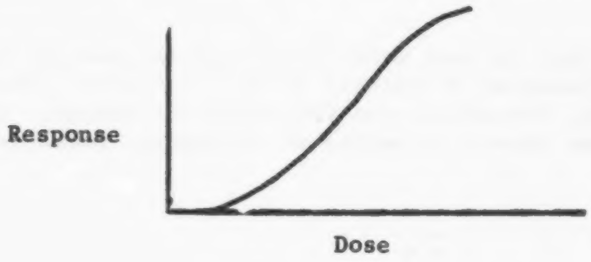

FIGURE I

Figure 2 represents a linear, or non-threshold relationship, in which the curve intersects the abscissa at the origin. Here any dose, no matter how small, involves some degree of response. There is some evidence that the genetic effects of radiation constitute a non-threshold phenomenon, and one of the underlying (and prudent) assumptions in the establishment of radiation protection guides and in radiation control activities in public health programs has been the existence of a non-threshold effect. Thus some degree of risk is assumed when large populations of people are exposed to even very small amounts of radiation. This assumption often makes the establishment of guidelines for acceptable radiation exposure an enormously complex task, since the concept of "acceptable risk" comes into play, in which the benefit to be accrued from a given radiation exposure must be weighed against its hazard.

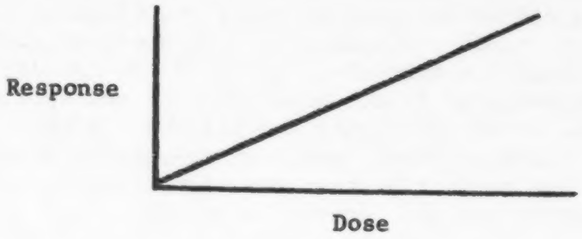

FIGURE 2

B. Rate of Absorption

The rate at which the radiation is administered or absorbed is most important in the determination of what effects will occur. Since a considerable degree of recovery occurs from the radiation damage, a given dose will produce less of an effect if divided (thus allowing time for recovery between dose increments) than if it were given in a single exposure.

C. Area Exposed

Generally when an external radiation exposure is referred to without qualification as to the area of the body involved, whole-body irradiation is assumed. The portion of the body irradiated is an important exposure parameter because the larger the area exposed, other factors being equal, the greater the overall damage to the organism. Even partial shielding of the highly radiosensitive blood-forming organs such as the spleen and bone marrow can mitigate the total effect considerably. An example of this phenemenon is in radiation therapy, in which doses which would be lethal if delivered to the whole body are commonly delivered to very limited areas, e.g. to tumor sites.

D. Variation in Species and Individual Sensitivity

There is a wide variation in the radiosensitivity of various species. Lethal doses for plants and microorganisms, for example, are usually hundreds of times larger than those for mammals. Even among different species of rodents, it is not unusual for one to demonstrate three or four times the sensitivity of another.

Within the same species, biological variability accounts for a difference in sensitivity among individuals. For this reason the lethal dose for each species is expressed in statistical terms, usually as the LD_{50} for that species, or the dose required to kill 50% of the individuals in a large population. For man, the LD_{50} is estimated to be approximately 450 R.

E. Variation in Cell Sensitivity

Within the same individual, a wide variation in succeptibility to radiation damage exists among different types of cells and tissues. In general, those cells which are rapidly dividing or have a potential for rapid division are more sensitive than those which do not divide. Futher, cells which are non-differentiated (i.e., primitive, or non-specialized) are more sensitive than those which are highly specialized. Within the same cell families then, the immature forms, which are generally primitive and rapidly dividing, are more radiosensitive than the older, mature cells which have specialized in function and have ceased to divide.

Based upon these factors, it is possible to rank various kinds of cells in descending order of radiosensitivity. Most sensitive are the white blood cells called lymphocytes, followed by immature forms of other white blood cells found in the bone marrow, and immature red blood cells. Epithelial cells, which line and cover body organs, are of moderately high sensitivity; in terms of injury from large doses of whole-body external radiation, the epithelial cells which line the gastro-intestinal tract are often of particular importance. Cells of low sensitivity include muscle and nerve, which are highly differentiated and do not divide.

IV. Short-term Effects

An acute dose of radiation is one which is delivered to a large portion of the body during a very short time. If the amount of radiation involved is large enough, acute doses may result in effects which can manifest themselves within a period of hours or days. Here the latent period, or time elapsed between the radiation insult and the onset of effects, is relatively short and grows progressively shorter as the dose level is raised. The signs and symptoms which comprise these short-term radiation effects are collectively known as the Acute Radiation Syndrome.

A. Stages in the Acute Radiation Syndrome

1. Prodrome

This is the initial phase of the syndrome, and is usually characterized by nausea, vomiting and malaise. It may be considered analogous to the prodrome stage in acute viral infections, in which the individual is subject to non-specific systemic reactions.

2. Latent Stage

During this phase, which may be likened to the incubation period of a viral infection, the subjective symptoms of illness may subside, and the individual may feel well. Changes, however, may be taking place within the blood-forming organs and elsewhere which will subsequently give rise to the next aspect of the syndrome.

3. Manifest Illness Stage

This phase reflects the clinical picture specifically associated with the radiation injury. Among the possible signs and symptoms are epilation, fever, infection, hemorrhage, severe diarrhea, prostration, disorientation, and cardiovascular collapse. Which, if any, of the foregoing phenomena are observed in a given individual is largely dependent upon the radiation dose received.

4. Recovery or Death

B. Relation of Dose to Type of Acute Radiation Syndrome

Recalling the different sensitivities of various kinds of cells, one can predict roughly the biological systems which will be affected as radiation dose increases. At relatively low doses, for example, the most likely cells to be injured are those with greatest sensitivity, i.e., immature white blood cells of lymph and bone marrow, so that the observable effects during the manifest illness stage would relate to these cells; one would thus expect to observe fever, infection and hemorrhage. This is known as the hematopoietic form of the acute radiation syndrome.

At higher doses, usually over 600 rads, cells of somewhat lower sensitivity will be injured. Of particular importance are the epithelial cells which line the gastrointestinal tract, for when these are destroyed a vital biological barrier is broken down. As a result, there may be fluid loss, overwhelming infection, and severe diarrhea in this gastrointestinal form of the acute radiation syndrome.

In the cerebral form, which may result from doses of 10,000 rads or more, the relatively resistant cells of the central nervous system are damaged, and the affected individual undergoes a rapid illness, characterized by disorientation and shock.

Considering the large degree of individual variation which exists with respect to radiation injury, it is difficult to assign a precise dose range to each of the above forms of the syndrome. The following generalizations, however, may serve to provide a rough indication of the kinds of doses involved. At 50 rads or less, ordinary laboratory or clinical methods will show no indications of injury. At 100 rads, most individuals show no symptoms, although a small percentage may show mild blood changes. At 200 rads, most persons show definite signs of injury; this dose level may prove fatal to those individuals most sensitive to the effects of radiation. At 450 rads, the median lethal dose has been reached, and 50 per cent of exposed individuals will succumb. Approximately 600 rads usually marks the threshold of the gastrointestinal form of the acute radiation syndrome, with a very poor prognosis for all individuals involved; a fatal outcome may well be certain at 800 to 1,000 rads. (For a detailed account of the Acute Radiation Syndrome, including symptomatology, laboratory findings, diagnosis and patient management, see: Thoma, George E., and Wald, Niel, "The Diagnosis and Management of Accidental Radiation Injury," Journal of Occupational Medicine, 1: 421-427, August 1959.)

C. Summary

1. The Acute Radiation Syndrome represents the signs and symptoms which result from large doses of radiation, generally over 100 rads, delivered to a major portion of the body; it is important to recall that this type of injury occurs only when the dose is received over a short period of time. The total effect may vary from mild and transient illness to death.

2. Because of the variation in succeptibility to radiation injury which exists among different individuals, it is extremely difficult to predict with accuracy the degree of effect in a given person, even when the dose is known. Within certain broad ranges, however, certain effects may be correlated with various dose levels on a population basis.

3. The course of the syndrome may vary from hours to several weeks. This time element is generally related to the radiation dose; other factors being equal, the duration of the various phases of the syndrome is inversely proportional to the amount of radiation received, with a rapid, fulminating illness being characteristic of very high doses.

V. Long-term Effects

A. Introduction

Long-term effects of radiation are those which may manifest themselves years after the original exposure. The latent period, then, is much longer than that associated with the acute radiation syndrome. Delayed radiation effects may result from previous acute, high-dose exposures or from chronic low level exposures over a period of years. From the standpoint of public health significance, the possibility of long-term effects on the large number of people receiving low, chronic exposures is cause for greater concern than the short-term radiation effects from acute exposures which involve only a few individuals.

It should be emphasized that there is no unique disease associated with the long-term effects of radiation; these effects manifest themselves in human populations simply as a statistical increase in the incidence of certain already-existing conditions. Because of the low normal incidence of these conditions, it is usually necessary to observe large populations of irradiated persons in order to measure this kind of increase, and employ biostatistical and epidemiologic methodology. In addition to the large numbers of people needed for human studies of long-term radiation effects, the situation is further complicated by the latent period; in some cases, a radiation induced increase in a disease may go unrecorded unless the study is continued for many years.

It should also be noted that although it is possible to perform true experiments with animal populations, in which all factors with the exception of radiation exposure are kept identical in study populations, human data is limited to "second hand" information, accrued from populations which have been irradiated for reasons other than radiobiological information. It is often the special characteristics of irradiated human populations, i.e., the presence of some pre-existing disease, which make it extremely difficult to draw meaningful conclusions when these groups are compared with non-irradiated ones.

Despite the above difficulties, many epidemiologic investigations of irradiated human beings have provided convincing evidence that ionizing radiation may indeed result in an increased risk of certain diseases long after the initial exposure. This information supplements and corroborates that gained from animal experimentation which demonstrates these same effects.

Among the long term effects thus far observed have been somatic damage, which may result in an increased incidence of cancer, embryological defects, cataracts, and lifespan shortening; and genetic mutations, which may adversely affect many generations after the original radiation damage.

B. Carcinogenic Effects

With proper selection of animal species and strains, and of dose, ionizing radiation may be shown to exert an almost universal carcinogenic action, resulting in tumors in a great variety of organs and tissues. There is human evidence as well that radiation may contribute to the induction of various kinds of neoplastic diseases.

1. Possible Mechanisms

It should be made clear that even with high doses of radiation, most irradiated individuals will not suffer long-term consequences despite the fact that the incidence of certain diseases, such as leukemia and other forms of cancer, may be increased many fold. The explanation lies in the fact that most diseases are probably "caused" by the simultaneous interaction of several factors, and that the presence of some of these factors without the others may not be sufficient to induce the disease. Radiation, like other chemical and physical agents which are considered carcinogenic, may be only one of a number of interacting factors which, in a given individual, must be present in order to result in the disease.

Among the tentative explanations thus far proposed for the carcinogenic action of radiation are the following:

a. The essential factor in the production of cancers may be a virus which attacks normal cells by injecting itself into the cell nucleus. The genetic material of the virus, now within the host cell, stimulates the cell to reproduce wildly, thus initiating the neoplastic growth. The virus, it would seem, is ubiquitous, and even may be passed from mother to fetus during prenatal life. It would follow, then, that normal cells have a natural mechanism whereby the action of these viruses is resisted; it is possible that radiation and other carcinogenic agents may activate the latent virus or interfere with the cell's resistance.(1) In this case, the presence of the virus in the tissue would be the primary, initiating event, and the radiation would act as a promoting agent.

b. Certain diseases, among them leukemia, have been associated with specific chromosome aberrations. It may be that radiation damage can produce these abnormalities in the chromosomes and that these changes in turn initiate the disease.(2)

c. Radiation can produce mutations in the somatic cells as well as the germ cells, and it may be that a sufficient accumulation of mutations in a colony of cells can result ultimately in the kind of uncontrolled growth which results in cancer. The somatic mutation concept is an attractive one since it provides a means by which to relate both the carcinogenic effects of radiation and aging. Somatic mutations probably occur constantly at a low rate in all organisms and the resultant damage accumulates gradually in the affected tissues. When the level of malfunction or damage reaches a critical point, cell death or carcinogenesis could occur. Radiation, like other harmful agents, may accelerate the rate at which these mutations occur, thus hastening the death of the organism or the production of cancers.(3)

When radiation doses are large enough to destroy a portion of the cells in an organ, the surviving cells, many of which may have undergone mutations as a result of the radiation exposure, are stimulated to rapid reproduction in order to replace the missing ones. This resulting rapid division may be a concomitant factor in cancer production.(4) In the somatic chromosome abberation or mutation processes, the radiation induced change may be the primary or initiating event, with other factors playing a contributory or promoting role.

d. As a result of the irradiation of water-molecules, which are abundant in all living cells, certain short-lived but potent damaging agents called free radicals are formed and may play an important role in both cancer and aging. There is some evidence that these radicals are generated continually at a low rate as a by-product of certain normal biochemical reactions in living cells, and that radiation simply accelerates their formation.(5)

None of the above speculations need exclude the others. That cancer, mutations and aging are interrelated seems reasonably clear, but the precise mechanisms involved have yet to be elucidated. One theory ties together several phenomena and holds that cancer evolves when a gentic mutation which predisposes an individual to cancer interacts during his lifetime with a sufficiently large number of accumulated somatic mutations (which can be produced by radiation) in the presence of a triggering agent, which could be a virus.(6)

2. Human Evidence

Both empirical observations and epidemiologic studies of irradiated individuals have more or less consistently demonstrated the carcinogenic properties of radiation. Some of these findings are summarized below.

a. Radium Dial Painters. Early in this century, when long-term radiation effects were little recognized, luminous numerals on watches and clocks were painted by hand with fine sable brushes, dipped first in the radium-containing paint and then often tipped on the lips or tongue. Young girls commonly were employed in this occupation. Years later, studies of these individuals who had ingested radium paint have disclosed an increased incidence of bone sarcomas and other malignancies, resulting from the burdens of radium which had accumulated in their bones.(7)

b. Radiologists and dentists. Some early medical and dental users of X-rays, largely unaware of the hazards involved, accumulated considerable doses of radiation. As early as the year 1910, there were reports of cancer deaths among physicians, presumably attributable to X-ray exposure. Skin cancer was a notable finding among these early practitioners;(8) dentists, for example, developed lesions on the fingers with which they repeatedly held dental films in their patients' mouths.

Although the excesses associated with the very early use of X-rays have diminished considerably, recent studies of radiologists have shown a statistically significant increase in the incidence of leukemia as compared with physicians who do not use radiation.(9) (10)A recent similar study with dentists disclosed no significant increase over expected rates.(11)

c. Uranium Miners. Early in this century, certain large mines in Europe were worked for pitchblende, a uranium ore. Lung cancer was highly prevalent among the miners as a result of the inhalation of large quantities of airborne radioactive materials. It was estimated that the risk of lung cancer in the pitchblende miners was at least 50% higher than that of the general population.(7)

Modern mining conditions have greatly improved. Nonetheless, recent studies have indicated a slight but statistically significant excess risk of lung cancer even among contemporary American uranium miners.(12)

d. Atomic Bomb Survivors. One of the strongest supports for the concept that radiation is a leukemogenic agent in man comes from the epidemiologic studies of the survivors of the atomic bombing in Hiroshima. Survivors exposed to radiation above an estimated dose of approximately 100 rem showed a significant increase in the incidence of leukemia. In addition, leukemia incidence correlated well with the estimated dose (expressed as distance from the detonation) thus strengthening the hypothesis that the excess leukemia cases were indeed attributable to the radiation exposure.(7) There is also some indication of an increase in thyroid cancer among the heavily irradiated survivors.(26)

e. Ankylosing Spondylitis Patients. Ankylosing spondylitis, a progressively disabling arthritic disease of the spine, can be treated with large X-ray doses delivered to the vertebrae to slow the progress of the disease and to relieve symptoms. Persons thus treated accumulated large doses of radiation to the bone marrow. A study of a large population of such persons revealed a much higher incidence of leukemia than might be expected in the general population.(7) That the observed leukemias were probably due to the radiation is attested to by a subsequent study in which the leukemia incidence for patients with arthritic diseases not treated with X-rays was ascertained; the authors conclude that the irradiation was probably a major factor in the excess leukemia found among the X-ray treated patients.(13)

f. Children Irradiated for Thymus Enlargement. Many young children with respiratory distress were diagnosed in former years as having enlarged thymus glands and were treated with therapeutic doses of X-rays to the thymic region. A number of follow-up studies were performed on these children, and although results varied, it is generally agreed that these persons have experienced a significantly increased incidence of thyroid cancer and other malignancies of the head and neck.(7) (14)Such findings are not limited to thymic irradiation; further studies (44)have demonstrated excess thyroid cancers and other head and neck malignancies as a result of childhood irradiation to this area of the body for the treatment of a wide variety of benign conditions such as enlarged tonsils and adenoids, acne, etc.

g. Polycythemia Patients. Polycythemia vera is a disease characterized by an excess of red blood cells which can be treated by the administration of phosphorus-32 internally. An epidemiologic study of patients thus irradiated seems to indicate a considerable excess of subsequent leukemias, compared with a control population consisting of non-irradiated polycythemia patients.(15)

h. Patients Treated by Pneumothorax. A link between high doses of radiation to the chest and breast cancer was discovered in a survey of women who had been treated for tuberculosis by artificial pneumothorax,(40)a procedure which consisted of intentionally collapsing the affected lung for a period of time and then reinflating it. This was accomplished with the assistance of the fluoroscope, and in many cases the pneumothorax treatment was repeated, sometimes more than 100 times. The patient was often positioned in the vertical fluoroscope machine facing the X-ray tube, so that the largest radiation dose was delivered to the anterior surface of the chest. The incidence of breast cancer among these heavily irradiated patients was found to be 4 to 8 times the expected rate for this disease. Further, the investigator was able to show a correlation between the side of the chest receiving the treatment and the affected breast.

i. Children of Mothers Irradiated During Pregnancy. A pioneering study in this area purported to show an increased risk of leukemia among young children if they had been irradiated in utero as a result of pelvic X-ray examination of the mother.(16) Mothers of leukemic children were questioned as to their radiation histories during pregnancy with the child in question, and these responses were compared with those of a control group, consisting of mothers of healthy playmates of the leukemic children. Originally this work received much criticism, based partly on the questionnaire technique used to elicit the information concerning radiation history. It was believed that differences in recall between the two groups of mothers might have biased the results. A larger subsequent study (17) designed to correct for the objections to the first one corroborated its essential findings, and established the leukemogenic effect on the fetus of prenatal X-rays.

It should be noted that the investigations presented thus far which demonstrate the carcinogenic properties of radiation involve large doses, such as those received in therapeutic X-ray procedures, with the exception of these childhood leukemia investigations. Here, doses of radiation are low, in the diagnostic radiographic range. Such findings bear out the high sensitivity of embryonic tissues to radiation damage. In evaluating human studies of the kind described above, two important concepts should be borne in mind.

(1) Because these studies were not designed as radiobiological experiments in which all factors are held constant with the exception of radiation exposure, caution is required before the association between radiation and some later disease can be labeled as a cause-effect relationship. This is particularly true when the study group consists of patients irradiated for some disease or abnormality, since the question arises as to whether the abnormality itself might not account for the later disease rather than the irradiation. Sometimes further studies or the selection of a proper control group with which to compare the irradiated subjects can help to resolve these doubts. For

example, in the spondylitis investigation, a valid question arose as to whether the disease itself might predispose the patient to develop leukemia later. A follow-up study which ascertained the leukemia incidence among non-irradiated rheumatic patients, helped to answer this question. The same question might have arisen in the polycythemia study, except that the control group in this instance consisted of persons with the disease who had not been treated with radiation. Doubts concerning the studies of children with thymic irradiation could have been forestalled, had the control group consisted of children with diagnosed thymic enlargement who had not been treated with X-rays. It was not possible, however, to select such a control group; instead healthy siblings or cancer incidence from general population statistics were employed. Thus, although the weight of evidence in these studies points toward true radiation carcinogenesis, there is room for speculation as to whether the infants with enlarged thymus glands might not have been at least somewhat predisposed to the development of malignant diseases. Even the studies of the relationship of prenatal X-ray examinations to childhood leukemias have been subject to the same kind of question, e.g., whether the special characteristics of the mothers and children in question which necessitated the pelvic X-rays in the first place might not be a predisposing factor in the development of leukemia, irrespective of or in addition to the radiation received. Despite these reservations, all of the above studies, when taken together, comprise an impressive accumulation of evidence indicating that ionizing radiation is a true carcinogen in man.

(2) Assuming that studies such as these are valid, the question arises as to their practical implications. Even in investigations such as the spondylitis and polycythemia studies in which roughly a ten-fold increase in leukemia was observed, the additional risk to an irradiated individual remains small because of the relatively low normal incidence of leukemia. The small but real increase in risk to the individual calls for an intelligent balancing, in each case, of the benefits to be accrued from the radiation exposure and the concomitant hazard. Valuable therapeutic and diagnostic X-ray techniques which are of great benefit to patients cannot be abandoned because of the risk of delayed harmful effects; on the other hand, if the same diagnostic information or therapeutic results can be obtained using techniques which reduce radiation exposure to the patient, or if equally effective non-radiologic procedures which do not involve such risk are available, such methods should be used.

C. Embryological Effects. Considering the fact that immature, undifferentiated, and rapidly dividing cells are highly sensitive to radiation, it is not surprising that embryonic and fetal tissues are readily damaged by relatively low doses of radiation. It has been shown in animal experiments that deleterious effects may be produced with doses of only 10 rads delivered to the embryo. There is no reason to doubt that the human embryo is equally susceptible.(19)

The majority of the anomalies which are produced by prenatal irradiation involve the central nervous system, although the specific type of damage is related to the dose and to the stage of pregnancy during which irradiation takes place. In terms of embryonic death, the very earliest stages of pregnancy, perhaps the first few weeks in the human beings, are most radiosensitive.(19) From the standpoint of practical radiation protection, this very early sensitivity is of great significance, because it involves a stage in human embryonic development in which pregnancy may well be unsuspected. For this reason, the International Committee on Radiological Protection has recommended that routine non-emergency diagnostic irradiation involving the pelvic area of women in the child-bearing years be limited to the 10-day interval following the onset of menstruation. Such precautions would virtually eliminate the possibility of inadvertantly exposing a fertilized egg.(20) This recommendation has been accepted in many countries, including Great Britain,(21) Germany,(22) Norway,(23) and Denmark,(24) among others. In a few countries, guidelines have also been formulated for therapeutic abortion when pelvic radiation doses during certain stages of pregnancy are estimated to exceed specified limits.(22) (24) (25)

For the production of congenital anomalies in the newborn, irradiation during the period of organogenesis is of greatest importance.(19) This period occurs during approximately the second through the sixth week of human gestation, when pregnancy could still be unsuspected. During this period, embryonic death is less likely than in the extremely early stage, but the production of morphological defects in the newborn is a major consideration.

During later stages of pregnancy, embryonic tissue is more resistant to gross and easily observable damage. However, functional changes, particularly those involving the central nervous system, may result from such late exposures(41) and would be difficult to measure or evaluate at birth. They usually involve subtle alterations in such phenomena as learning patterns and development and may have a considerable latent period before they manifest themselves.(17) There is some evidence that the decreasing sensitivity of the fetus to gross radiation damage as pregnancy progresses may not apply for the leukemogenic effects of prenatal irradiation.(16) (28) Another important factor to be considered in evaluating the radiation hazard during late pregnancy is that irradiation may produce true genetic mutations in the immature germ cells of the fetus for which no threshold dose has been established.(19)

It should be emphasized that radiation is not unique in producing embryological effects and that a growing body of evidence exists which indicates that a host of external insults, including certain drugs, chemicals, and viral infections, also can damage the highly sensitive embryo and fetus.

Human evidence for embryological damage has been found among persons exposed in utero at the time of the atomic bombing of Hiroshima. Data obtained from their follow-up through childhood and adolescence into adulthood, in which groups exposed during gestation were compared with each other and with non-exposed controls on the basis of distance from the detonation and stage of pregnancy, shows a growth stunting effect among the exposed, particularly as regards head size, and an increased incidence of mental retardation.

The incidence of these developmental defects correlates well with proximity to the bomb and thus with estimated dose; also, the results further corroborate the increased sensitivity to embryological damage during the first trimester of pregnancy.(29)

D. Cataractogenic Effects. The fibers which comprise the lens of the eye are specialized to transmit light. Damage to these, and particularly to the developing immature cells which give rise to them, can result in opacities in the lens called cataracts, which, if they are large enough, can interfere with vision. Radiation in sufficiently high doses can induce the formation of cataracts; the required dose for humans, which is difficult to ascertain, probably is in the order of several hundred rads for X or gamma rays, and 1/5 to 1/10 of this for neutron irradiation.(7)

Human evidence for radiation cataractogenesis is derived mainly from a relatively small number of workers inadvertently exposed to large doses of radiation to the eye,(7) including several nuclear physicists working with cyclotrons; patients exposed to therapeutic radiation (sometimes from radium plaques applied to the eye);(7) and Japanese atomic bomb survivors who were heavily irradiated.(7) (30)

E. Lifespan Shortening. In a number of animal experiments radiation has been demonstrated to have a lifespan shortening effect. The aging process per se is complex and largely obscure, and the exact mechanisms involved in this effect are as yet uncertain. Irradiated animals in these investigations appear to die of the same diseases as the non-irradiated controls, but they do so at an earlier age. (7) How much of the total effect is due to premature aging and how much to an increased incidence of radiation-induced diseases is still unresolved. (7)

1. Mechanisms. A number of theories have been proposed to account for the phenomenon of aging in general, and for the aging effects of radiation in particular. One theory (7) is that a variety of extrinsic insults produce tissue damage in organisms, some of which is reparable and some of which is irreparable. The irreparable, or residual components of various insults to the organism (infections, trauma, etc.) are additive and cumulative, and when a certain critical amount of injury has accumulated, the organism dies. Because irradiation is one of the agents which can produce such injury, irradiated animals arrive at a lethal accumulation sooner than do the non-irradiated controls. Another theory (31) proposes that radiation exerts its lifespan shortening effect by producing somatic mutations in the cells, which lower the organism's ability to function properly. It further states that organs having cells which seldom, if ever, divide are affected most by these mutations, and play a major part in the aging process.

2. Human Evidence. A study of the possible lifespan shortening effect of radiation in British radiologists yielded negative results. (32) On the other hand, an investigation of American radiologists, as compared with physicians not using radiation, appeared to show that radiologists die approximately 5 years sooner than their non-radiological counterparts. (33) A follow-up study, however, indicated that proper age correction factors had been ignored in the original work, and that when these were applied the lifespan differences disappeared. (34) A more recent American study, (35) in which death rates from various causes were established for radiologists and for two control groups, consisting of physicians who used radiation somewhat and those who did not use it at all, seems to show a true lifespan shortening effect among the radiologists. An association, of course, between two phenomena (in this case, being a radiologist and having a shorter lifespan than a non-radiologist) does not necessarily indicate that one is a cause of the other, and recalling the caution with which epidemiologic studies must be interpreted one might propose explanations for the association other than

that the radiation causes the shortened lifespan. It is conceivable, for example, that those individuals choosing radiology as a specialty could be somewhat less healthy as a group than those selecting other fields, and thus a slightly shorter lifespan among the former would not necessarily relate to their radiation exposure. The authors have considered such alternative explanations of the data, however, and, because of certain strengthening factors in their findings, they nonetheless hold that a true lifespan shortening effect was operative. An important finding in this study, which helps to support the general adequacy of current occupational radiation protection guidelines, is that the excess risk of death among the radiologists is largely confined to those who practiced during the earlier years of X-ray use when safety practices were more lax and occupational exposures among radiologists were presumably much higher than today.

F. Genetic Effects

1. Background

The fertilized egg, which is a single cell resulting from the union of sperm and egg, and which after millions of cell divisions results in a new organism, contains all of the genetic information necessary to produce all of the organs and tissues of the new individual. This information is carried in the nucleus of the fertilized egg on rod shaped structures called chromosomes, arranged in 23 pairs. In each pair, one member is contributed by the mother and the other by the father. With each cell division which the rapidly developing embryonic tissue undergoes, all of this information is faithfully duplicated, so that the nucleus in each cell of the new organism contains essentially all of the information. This, of course, includes those germ cells in the new organism which are destined to become sperm and egg, and thus the information is transmitted from one generation to the next. This hereditary information is often likened to a template, or to a code, which is reproduced millions of times over with remarkable accuracy. It is possible to damage the hereditary material in the cell nucleus by means of external influences, and when this is done the garbled or distorted genetic information will be reproduced just as faithfully when the cell divides as was the original message. When this kind of alteration occurs in those cells of the ovaries or testes which will become mature sperm and egg, it is referred to as genetic mutation; if the damaged sperm or egg cell is then utilized in conception, the defect is reproduced in all of the cells of the new organism which results from this conception, including those which will become sperm or egg, and thus whatever defect resulted from the original mutation can be passed on for many generations.

Most geneticists agree that the great preponderance of genetic mutations are harmful.(36) By virtue of their damaging effects, they can be gradually eliminated from a population by natural means, since individuals afflicted with this damage are less likely to reproduce themselves successfully than normal individuals. The more severe the deficit produced by a given mutation, the more rapidly it will be eliminated, and vice-versa; mildly damaging mutations may require a great many generations before they gradually disappear.(37)

As a balance to this natural elimination of harmful mutations, fresh ones are constantly occurring. A large number of agents have mutagenic properties, and it is probably that our current knowledge includes just a fraction of these.(38) In addition, it may be that mutations can arise within the germ cells of an organism without external insult; free radicals, which may be produced as a natural by-product of normal metabolic reactions in the body, may have a mutational effect.(5) Among the various external influences which have been found to be mutagenic are a wide variety of chemicals, certain drugs, and physical factors such as elevated temperatures and ionizing radiation. Natural background radiation probably accounts for a small proportion of naturally occurring mutations. For man, it has been estimated that background radiation probably produces less than ten per cent of these.(39)Man-made radiation, of course, if delivered to the gonads, can also produce mutations, over and above those which occur spontaneously. Radiation, it should be noted, is not unique in this respect, and is probably one of a number of man-made environmental influences which is capable of increasing the mutation rate.

2. Observing Mutations

Measuring changes in the normal mutation rate in humans is extremely difficult for several reasons. First, the majority of mutations are recessive, that is, their full effects do not manifest themselves in an individual unless he carries the same mutational defect in the same location on a given pair of chromosomes, i.e., unless both his mother and father were afflicted with the same kind of genetic damage.(7) It can be seen from this that it might take many generations after a genetically damaging event occurred in a population before enough individuals carrying the recessive mutation mated with one another to produce offspring who would demonstrate overt damage. Secondly, contrary to popular impression, the damage produced by most mutations is subtle in its effects and difficult to measure. Mutations, for example, may result in a slightly altered metabolism, in which there is a less efficient utilization of certain nutritional elements, or a slightly greater predisposition to a given disease, or a slightly lower intelligence than would otherwise have been attained.(7) Adding to this is the difficulty encountered in extricating true genetic phenomena from other influences which may produce the same results. It would be most difficult, for example, to determine whether an individual's predisposition to heart disease were due to a subtle genetic defect in his cardiovascular system, or to environmental stresses such as diet or occupation, or to personality and developmental factors in childhood, etc.

Despite these difficulties, it is possible to observe fluctuations in the mutation rate if large enough populations are available for close study. Certain diseases, for example, have been linked to specific genetic defects, and an increase or decrease in the incidence of these diseases would indicate a concomitant change in the mutation rate. Certain mutations are lethal; they are highly damaging and result in intrauterine death. Other factors being equal, significant fluctuations in the incidence of these deaths in a population might serve as a rough barometer of changing mutation rates. Observing a population for evidence of genetic mutations can be likened to watching an iceberg; most of the iceberg is invisible, with only a small portion above the water. Changes in the size of the observable part serve to give some indication of the more significant changes taking place beneath the surface. (For a discussion of the difficulties and techniques in finding and evaluating genetic radiation damage, see Chapter 7, "The Quantitative Assessment of Hereditary Damage Induced by Radiation," by James and Newcombe, in "Progress in Medical Genetics," Vol. 3, Grune and Stratton, Inc. New York, 1964.)

Even in the first generation after a population has been exposed to a possibly mutagenic event, it is possible to observe the effects of certain kinds of mutations. Dominant mutations, i.e., those which manifest their full effects even when only one parent carries the mutation, may be evident in the offspring. Those which are also lethal will appear as an increase in intra-uterine deaths. There is a particular kind of recessive mutation which can also be observed in the first generation, the sex-linked mutation. Of the 23 pairs of chromosomes in the fertilized egg, one pair determines the sex of the offspring. In this pair, females carry two full-sized chromosomes, called X-chromosomes, while males carry one X chromosome and one Y chromosome, which is much smaller and which probably does not carry a full compliment of genetic information. If a recessive mutation arises on one of the X chromosomes of the mother, female offspring who inherit it, but who have the benefit of the matching normal X chromosome of the father, will not demonstrate this recessive characteristic. Male offspring however, to whom the mother has contributed this defective X chromosome, have only the small Y chromosome contributed by the father to offset the deficit, and as a result the damage will appear in these males, despite its having been produced by a recessive mutation. Recessive sex-linked mutations of this kind which are also lethal will thus show up as an increase in the number of intra-uterine deaths among boys, and not among girls. This provides a useful yardstick for assessing genetic damage in an irradiated population, for if a sub-population is selected in which mothers have been irradiated and fathers have not, then a lowering in the percentage of boys born versus girls, i.e., a reduction in the sex-ratio, might be an indicator of genetic damage.

3. Animal Evidence

The mutagenic properties of ionizing radiation were first discovered in 1927, using the fruit-fly as the experimental animal. Since that time, experiments have been extended to include other species, and a great deal of recent investigation has been carried out on the mouse. Animal experimentation remains our chief source of information concerning the genetic effects of radiation, and as a result of the intensive experimentation which has been carried out during recent years, certain generalizations may be made.(7) Among those of health significance are (1) that there is no indication of a threshold dose for the genetic effects of radiation, i.e., a dose below which genetic damage does not occur, and (2) that the degree of mutational damage which results from radiation exposure seems to be dose-rate dependent, so that a given dose is less effective in producing damage if it is protracted or fractionated over a long period of time.

4. Human Evidence

a. A major human study on genetic effects has concerned the Japanese atomic bomb survivors. As the index of a possible increase in the mutation rate, the sex-ratio in the offspring of certain irradiated groups (families, for example, in which the mother had been irradiated but the father had not) was observed, using the approach described earlier. Assuming that some of the mutational damage in the mothers would be recessive, lethal and sex-linked, a shift in the sex-ratio among these families might be expected in the direction of fewer male births than in completely non-irradiated groups, and this seemed to be the case in early reports.(7) Later evaluation of more complete data, however, did not bear out the original suggestion of an effect on the sex-ratio.(43)

b. The pre-conception radiation histories of the parents of leukemic children as compared with those of normal children was a part of the subject of another investigation.(28) From the results, it would appear that there is a statistically significant increase in leukemia risk among children whose mothers had received diagnostic X-rays during this period. The effect here is apparently a genetic rather than an embryologic one, since the irradiation occurred prior to the conception of the child.

A somewhat similar study ascertained the radiation exposure histories of the parents of children with Mongolism; most of this exposure too, was prior to the conception of the child.(42) A significantly greater number of the mothers of Mongoloid children reported receiving diagnostic fluoroscopy and X-ray therapy prior to the birth of the Mongoloid child than did mothers of normal children comprising a control group.

The findings of these two studies serve to provide additional evidence that ionizing radiation is a mutational agent in man. On the other hand, they can be viewed with the same kind of reservations as were explained previously, i.e., there could be significantly differences to begin with between populations of people requiring X-rays and those not requiring X-rays; these differences alone might account for a slightly higher incidence of leukemia or Mongolism in the offspring of the former group, irrespective of the radiation received.

5. Health Significance of Genetic Mutations

Recalling the previous discussion concerning the natural elimination of harmful mutations and the simultaneous introduction of fresh ones into a population, the total number of mutations present may be likened to the water in a tank, in which in-flow at the top represents new mutations and out-flow at the bottom represents the eliminations of old mutations. The water level does not necessarily remain constant; if the rate at which new mutations are produced exceeds that at which old ones are discarded, the pool of mutations grows larger. The reverse is true if the output exceeds the input with a resultant lowering of the pool. With contemporary human populations, it is highly desirable to keep the level of the mutational pool as low as possible, since the pool largely represents diseases and defects which tend to lower overall biological fitness. However, two factors unique to modern life may tend to increase the level. First, human populations are being exposed to a greater and greater number of potential mutagens as a result of a progressive increase in the variety and quantity of man-made chemical and physical agents which are a product of our technological advances. Secondly, modern medical knowledge and techniques result in the salvage of more and more individuals with genetic defects so that they may reproduce themselves, thus distributing these defects to an ever larger number of people. In the face of these factors which tend to increase the mutational load in the world's population, it is all the more important, if the level of the pool is to be kept at a minimum, to make every effort to maintain the influx of new mutations as small as possible. Considering the potent mutagenic properties of ionizing radiation, the goal, then, is clear: to avoid any unnecessary irradiation of the gonads.

This material was prepared by Mr. Mark Barnett of the Training and Manpower Development Program, National Center for Radiological Health.

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Radiation Protection Guides

I. PHILOSOPHY OF RADIATION PROTECTION

The setting and execution of guidelines for radiation protection are based upon an underlying philosophy in which two factors are of prime importance. First is the assumption that radiation effects follow a linear, or non-threshold dose-response relationship. There is convincing evidence, particularly insofar as the genetic effects of radiation are concerned, that there exists a non-threshold phenomenon; and although positive proof is thus far lacking, it has been deemed prudent to adopt this more conservative hypothesis in setting protection standards for large numbers of people. According to the non-threshold concept, there is no radiation dose so small that it does not involve some degree of risk. The non-threshold relationship, therefore, implies that there is no radiation protection guideline, no matter how low, which can insure absolute safety to every individual in a large population receiving the guideline dosage. However, since the magnitude of the risk is proportional to the dose received, untoward effects would become manifest at very low dose levels only if extremely large numbers of exposed individuals were observed.

The second major factor to consider is that radiation, like many other developments of modern life (such as the automobile) confers great benefit upon both society and the individual along with its risk to health. Consideration of the extent of these benefits makes a certain degree of risk acceptable. Thus, a balance must be struck in each contemplated radiation usage, in which the benefit to be gained is weighed against the anticipated risk. If the benefit outweighs the risk, the radiation is utilized so that its maximum benefit will be realized while human exposure will be maintained at the minimum consistent with deriving these benefits. The overall public health philosophy, then, is to attain maximum advantage from the use of ionizing radiation while minimizing concomitant exposure, that is, eliminating wherever possible all unnecessary exposure to radiation.

The Radiation Protection Guide (RPG) may be defined as the radiation dose which should not be exceeded without careful consideration of the reasons for so doing. In light of the non-threshold phenomenon, every effort should be made to encourage the maintenance of radiation exposures as far below the guide as practicable. Methods of estimating guides are primarily based on past experience in which individuals have been exposed to radiation for various reasons and upon animal experiments which have contributed greatly to the study of the effects of radiation. From this combined knowledge and from an understanding of the relative biological damage produced by various types of radiation, protection guides for whole-body exposure and for various organs have been recommended. These guides, of course, represent doses far below those at which any effects have thus far been observed.

II. BASIS FOR RADIATION PROTECTION GUIDES

Establishment of "safe" levels of long-term radiation dose requires knowledge of the cause-effect relationship between radiation dose and biological damage. Such damage may appear many years after initial exposure and is usually indistinguishable from the normal diseases and impairments of man. Information accumulated on this subject is, therefore, difficult to evaluate and is often controversial. Nevertheless, observations involving man and animal life have resulted in the accumulation of significant data. These include:

A. Genetic Effects

1. Studies involving fruit flies and mice
2. Hiroshima and Nagasaki populations (inconclusive)

B. Incidence of Neoplasms

1. Bone tumors in radium dial painters
2. Leukemia in radiologists
3. Thyroid carcinoma in children irradiated in infancy
4. Various neoplastic diseases, including leukemia, in patients receiving therapeutic radiation for a variety of reasons
5. Leukemia in offspring of mothers irradiated during pregnancy
6. Leukemia in survivors of Hiroshima and Nagasaki bombings

C. Life-Span Shortening

1. Studies with various animal species.
2. Radiologists vs. other physicians.

Evaluations of these observations in terms of allowable radiation dose to man is an exceedingly complex task. The National Council on Radiation Protection and Measurements (NCRP) has accepted the task and over the past 30 years has established recommendations regarding maximum permissible doses. Because of the fragmentary evidence currently available, the NCRP points out that these levels are not necessarily completely safe limits but rather levels which should carry an acceptable risk.

In 1959, the Federal Radiation Council was formed to provide a Federal policy on human radiation exposure. This organization published its first report in May, 1960. Its recommendations were essentially the same as those of the NCRP and the International Commission of Radiological Protection (ICRP). The Council suggested, however, that the terms "Radiation Protection Guides" replace the former "Maximum Permissible Doses." The newer terminology recommended by the Federal Radiation Council is used throughout this lecture outline.

III. CURRENT RECOMMENDED DOSE LIMITS

Radiation Protection Guides vary depending on whether the whole body or only a portion thereof is exposed and whether radiation workers or the general public is involved.

A. Radiation Workers

1. ACCUMULATED DOSE (EXTERNAL SOURCES)

a. For external exposure to the whole body, the maximum average dose rate should not exceed 5 rems per year. The same dose rate applies to the head and trunk, active blood-forming organs, the gonads, and the lenses of the eyes.

No occupational dose is allowed persons under 18 years of age. The accumulated dose at any subsequent age, therefore, should not exceed 5(N-18) rems where N is the age of the worker in years.

b. Generally, however, where only a single portion of the body is exposed, Radiation Protection Guide average dose rates are higher. For example, it is recommended that the average dose rate to the hands and forearms and to the feet and ankles should not exceed 75 rems per year.

2. ACCUMULATED DOSE (INTERNAL SOURCES)

a. Certain elements, upon ingestion, inhalation, etc., deposit uniformly throughout the body. Radioisotopes of these elements deliver a dose to the whole body. The Radiation Protection Guide dose rate for whole-body exposure from such radionuclides has the same limit as from external sources (i.e., 5 rems per yr.). No occupational exposure is allowed persons under 18 years of age.

b. Other radionuclides tend to localize in one or more selected body organs. Based on the essentiality of the organ to proper body function, epidemiological experience with radium, and genetic considerations, other Radiation Protection Guides have been specified for selected critical body organs.

(1) For most individual organs, it is recommended that the maximum average dose rate not exceed 15 rems per year.

(2) For the thyroid and skin, the maximum average dose rate should not exceed 30 rems per year; for the gonads, the average dose rate should not exceed 5 rems per year.

(3) For compact bone, the maximum permissible dose rate is limited to the average dose rate which would result from a body burden of 0.1 microcurie of radium. (This amount of radium would yield a dose rate of approximately 28 rems per year.)

B. General Population Groups

Recommended Radiation Protection Guides for the general population are considerably below those for radiation workers. One of the reasons for this stricter limitation on allowable dose is related to the possibility of genetic effects from radiation exposure. Because the general population contains all of the germ plasm controlling the genetic viability of the race, any mutational effects on this population would have a far greater total impact than exposure of that small segment of the population working with radiation.

Currently it is recommended that the yearly radiation exposure of individuals in general population (exclusive of natural background and the deliberate exposure of patients by dentists and doctors) should be held to one-tenth of the permissible occupational levels. Thus, for whole-body exposure of individuals in the general population, the radiation dose should not exceed 0.5 rem per year.

Exposure of the total population (this includes radiation workers and special groups, as well as the general population) presents a different problem. Here, it is necessary to make assumptions concerning the relationship between the recommended Radiation Protection Guide of 0.5 rem per year for individuals in the general population, and the average dose received by average total population groups. The Federal Radiation Council suggests the use of the arbitrary assumption that the majority of individuals do not vary from the average by a factor greater than three. Thus, they recommend the use of 0.17 rem as a Radiation Protection Guide for yearly whole-body exposure of average total population groups. This is in keeping with their recommendation that the average genetically significant dose to the total population not exceed 5 rems up to age 30 (exclusive of natural background and purposeful exposure of patients by practioners of the healing arts).

Assessment of the amount of radiation dose received by a given individual or population group requires totalling the doses received from external and internal sources. External exposures may be measured with a sufficient degree of accuracy by direct roentgen-rate monitoring procedures. Internal doses are assessed in terms of the concentration of specific radionuclides in air, water, milk, and food which may be inhaled or ingested. To enable comparison of the radioactivity concentrations measured in these various environmental phases with Radiation Protection Guides, concentration values[1] which are related to the established RPG have been derived for many radionuclides.

C. Factors Influencing Radioactivity Concentration Guides

The Radioactivity Concentration Guide is the concentration of radioactivity in the environment which is determined to result in whole-body or organ doses equal to the RPG. In calculating RCG values for a given radionuclide, the following factors must be taken into consideration:

1. INITIAL BODY UPTAKE

Large fractions of some elements are absorbed when taken into the body. In the case of certain other elements, only small fractions are absorbed in passage through the gastrointestinal tract.

Therefore, the greater retention would increase the hazard from the first group as compared with the second, other factors being equal.

When radionuclides are inhaled, unless information specific to the radionuclide is available, it is assumed, in the case of soluble compounds, that 25 percent is retained in the lower respiratory tract. From here, the nuclides move into the blood stream and a portion of each is deposited in its critical tissue within a few days. Approximately 50 percent is held in the upper respiratory tract and is swallowed. In the case of insoluble compounds, it is assumed that 12 percent is retained in the lower respiratory tract, which is usually taken as a critical organ. The remainder is eliminated by exhalation and swallowing.

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[1] Concentration values are expressed in terms of Radioactivity Concentration Guides (RCG) or Maximum Permissible Concentrations (MPC).

2. FRACTION RETAINED IN THE BODY

The rate of elimination from the blood and tissues of the body varies considerably for different elements or compounds. The time required for one-half of the original quantity of radioactive material to be removed from the body by biological processes is called the biological half-life.

Some materials in the blood stream are eliminated rapidly from the body whereas large fractions of others remain in the body organs. For example, radium, plutonium, and strontium are deposited in the bone where the rate of turnover is very slow; i.e., the biological half-life is many years. Radioisotopes of these elements are much more hazardous than those of carbon, sodium, and sulfur which have biological half-lives of a few days or weeks. The principal biological methods of elimination of radionuclides from the body are the urine, feces, exhalation, and perspiration. Usually elimination is much more rapid before the radionuclide is translocated from the body to a more permanent area, such as the bone. This time is usually from a few days to a few weeks. After the initial period, the elimination rate becomes more nearly exponential, and the application of the term "biological half-life" has more meaning.

3. ORGAN OR TISSUE IN WHICH RETAINED[2]

a. Radiosensitivity - Certain body organs or tissues are more radiosensitive than others. For example, the lymphatic tissue and bone-marrow are much more radiosensitive than muscle or nerve tissue. Therefore, in equal concentrations, an element like plutonium is more hazardous than uranium because the plutonium concentrates in the most sensitive part of the bone, whereas the uranium goes to other portions of the bone, to the kidneys, and to other relatively insensitive organs.

b. Size - For a given number of microcuries of a radionuclide in a critical organ, the smaller the organ the greater the concentration and the greater the dose delivered to the critical tissue. Iodine presents a much greater problem than sodium, since the iodine is very selectively absorbed in a much smaller organ, the thyroid gland, whereas sodium is rather uniformly distributed throughout the whole body. In many cases the radionuclide is deposited in a large organ but localized in a small portion of that organ, so that, in effect, the mass of the critical tissue may become very small.

c. Essentiality - Some organs are either not essential to the body function, or, when they are damaged or removed, special steps can be taken to supplement or compensate for their reduced function. For these reasons damage in some cases to the bone-marrow, kidneys, eyes, etc., may represent a greater hazard than equal tissue damage to the thyroid gland.

4. PHYSICAL PROPERTIES OF THE RADIONUCLIDE

a. Type and Energy of Radiation - The hazard is proportional to the relative biological effectiveness or quality factor of the radiation; e.g., alpha radiation is more damaging than beta radiation for a given energy of radiation. As the energy of the radiation is increased, the damage also increases.

b. Half-Life - The shorter the physical or radioactive half-life of a radionuclide, the less is the biological hazard. The radioactive half-life and the biological half-life may be combined into a single "effective" half-life by means of the formula:

$$T_{eff} = \frac{(T_r) \times (T_b)}{T_r + T_b}$$

D. Calculations of Radioactivity Concentration Guides

As an example of the approach used in determining RCG values, the case of cesium-137 is illustrated.

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[2] In certain instances, an organ of the body, such as the GI tract or lung, may receive a significant dose due to the mere presence of the radionuclide in material inhaled or ingested. Under these circumstances, the organ so exposed (even though not absorbing the radionuclide) may become the "criticial" organ.

1. The element cesium is distributed rather uniformly throughout the body. Therefore, an RPG for the radiation worker of five rems per year is selected for any radioisotope of this element.

2. Experimental and theoretical studies have shown that the presence in the body of 30 microcuries of ^{137}Cs will yield a whole-body dose rate of five rems per year. This quantity, 30 microcuries, is referred to as the "maximum permissible body burden" for ^{137}Cs.

3. If, however, 30 microcuries of ^{137}Cs were deposited within the body, they would not remain there long because of biological elimination and radioactive decay. Therefore, a certain amount could be ingested continually without exceeding the maximum permissible body burden.

4. A "standard man" consumes approximately 2200 milliliters of water per day. Approximately one-half of this is ingested during the working hours. If the daily intake of ^{137}Cs via drinking water is to be limited such that the "maximum permissible body burden" will not be exceeded (and the average yearly radiation worker whole-body dose rate not exceed five rems), then the concentration of this nuclide in drinking water must not exceed 4×10^{-4} microcuries per milliliter. This value, 4×10^{-4} Ci/ml, is the Radioactivity Concentration Guide (RCG) for ^{137}Cs in drinking water for consumption by radiation workers, based on an eight-hour per day, 40-hour work week for a radiation worker.

In a similar manner, it can be shown that an average concentration of 6×10^{-8} Ci/ml soluble ^{137}Cs in air in the working environment would result in a worker receiving a whole-body dose rate of five rems per year.

E. Standardization of Calculations

When efforts were first made to establish permissible body burdens and Radioactivity Concentration Guide values for the various radionuclides, it became evident that it would be difficult, if not impossible, to compare suggested values from the different laboratories unless all used the same basic assumptions relative to the average man. Most of the calculations were based on the same fundamental physical assumptions relative to the energy schemes and radioactive half-life values, but each person making these calculations used his own preferred values for the mass and effective radius of the body organs, the rates of ingestion and inhalation, elimination rates, etc. This difficulty was recognized at several major conferences. As a consequence certain characteristics of the so-called "standard man" were agreed upon.

F. Graded System of Actions

It was felt by the Federal Radiation Council that a commitment to the single values represented by the Radioactivity Concentration Guides might prove arbitrary and inflexible, and not provide adequate guidance for taking assessment and control actions appropriate to the risk involved. Therefore, the Council's Report No. 2 introduced the concept of graded scales of RANGES of action in which average daily intake of a radionuclide by samples of exposed population groups are listed in three ranges. These ranges apply to certain selected radionuclides of health significance, namely, radium-226, strontium-89, strontium-90, and iodine-131. In general, the single radioactivity concentration guide equivalent corresponds to the upper limit of RANGE II. For intakes in RANGE I, the Council guideline recommends periodic, confirmatory surveillance as necessary; for RANGE II, quantitative surveillance and routine control is indicated; and for RANGE III, the Council advises evaluation and application of control measures as necessary.

G. Protective Action Guides

All of the foregoing guidelines are predicated upon the more or less constant release of low-level radioactivity into the environment from the routine uses of radiation, and assume continuous radionuclide intake by the population. Control, then, is based primarily at the source. There are cases, however, in which the contamination of the environment might be accidental or unforeseen, producing contamination which is transient and not likely to recur; these might include reactor incidents which result in relatively high but temporary local radioactivity levels, for example. In cases of this kind, the "contaminating event" would not occur on a regular basis, and control, or protective action, might be based upon limiting or changing the intake of certain contaminated foods by the population. However, the impact of such measures upon the community which they are designed to benefit requires careful consideration by responsible authorities to insure that the benefit of the action taken is not outweighed by its other effects. To deal with this kind of situation, the Council, in its Reports No. 5 and No. 7, introduced the Protective Action Guide concept. The PAG is defined as the projected absorbed dose to individuals in the general population which would warrant protective action following a contaminating event. It is assumed that the corresponding projected dose to a suitable sample of the exposed population would be one-third of the PAG. These guidelines have, thus far, been established for iodine-131, strontium-90, and cesium-137. It should be noted that a decision to take action to limit a community's intake of an important basic food item containing radionuclides involves a balancing of the health benefits to be attained against the undesirable features of the protective action, such as disruption of dietary habits and nutritional needs. It follows, then, that control actions could be employed at dose levels above or below the PAG, depending upon the degree of total impact which the action has upon the community.

V. SUMMARY

Based on current information, Radiation Protection Guides for radiation dose have been recommended. These levels are subject to modification as more knowledge is gained. In view of their status and the possibility that any radiation dose may be damaging, it is well to recall the definition of the Radiation Protection Guide as that radiation dose which should not be exceeded without careful consideration of the reasons for doing so. Every effort should be made to encourage the maintenance of radiation doses as far below the Guide as practical.

Table 1 summarizes the current recommendations of the ICRP and the Federal Radiation Council.

Table 1. Radiation Protection Guides

Type of Exposure	Condition	Dose[1] (rem)
Radiation worker:	Accumulated dose	Five times number of years beyond age 18
(a) Whole body, head, and trunk, active blood-forming organs, gonads, or lens of eye	13 weeks	3
(b) Skin of whole body and thyroid	Year	30
	13 weeks	10
(c) Hands and forearms, feet and ankles	Year	75
	13 weeks	25
(d) Bone	Body burden	$0.1\ \mu Ci$ of ^{226}Ra or its biological equivalent
(e) Other organs	Year	15
	13 weeks	5
Population:		
(a) Individual	Year	0.5 (whole body)
(b) Average	30 years	5 (gonads)

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[1] Minor variations from other recommendations are not considered significant in light of present uncertainties.

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Basic Principles of Radiation Protection

I. INTRODUCTION

Application of the basic principles for protecting personnel from ionizing radiation will vary quantitatively, depending upon type, intensity, and energy of the radiation source. For example, beta particles from radioactive materials require less shielding than high speed electrons from a high-energy particle accelerator. Ideally, application of these protection principles would reduce radiation exposure to zero, but usually cost and convenience make a compromise necessary. The maximum permissible exposure levels serve as upper limits of this compromise.

II. EXTERNAL RADIATION HAZARDS

A. X Rays and Gamma Rays

X rays and gamma rays constitute the most common external radiation hazards. When they are of sufficient energy, both can penetrate deep into the body. No radiosensitive organ is beyond the range of their damaging powers. The most common source of x rays is, of course, the x-ray machine. Some x rays are also generated as a by-product of certain atomic and nuclear reactions. Gamma-ray sources include nuclear reactors, particle accelerators, and radionuclides. X-ray machines can usually be treated as point sources; this simplifies protective measures somewhat. Gamma-ray sources may or may not be point sources.

B. Beta Particles

Beta particles may constitute an external hazard if they have enough energy to penetrate to the basal layer of the epidermis. Those particles which are stopped by the horny layer of the skin are not external hazards. Radioactive nuclides and high-energy particle accelerators may be sources of beta radiation.

C. Neutrons

Neutrons, because of their penetrating powers, are considered external radiation hazards. They are produced in abundant quantities by high-energy particle accelerators and nuclear reactors. Small sources--such as radium-beryllium capsules--also produce neutrons. Neutrons are perhaps the most dangerous of all external radiation because they can cause much tissue damage and have so far proved to be the most difficult to monitor.

D. Protons and Deuterons

High-energy protons and deuterons are dangerous external radiation hazards due to their high ionizing powers. Fortunately, high-energy particle accelerators which produce them are few in number.

III. CONTROL OF EXTERNAL RADIATION HAZARDS

A. Distance

Distance is a very effective, and in many instances the most easily applied, method of radiation protection. Beta particles of a single energy have a finite range in air. Sometimes the distance afforded by the use of remote control handling devices will give complete protection.

The inverse square law for reduction of radiation intensity applies to point sources of x, gamma, and neutron radiation. (X-ray tubes act enough like point sources for reduction calculations by this law to hold valid. Gamma ray sources whose dimensions are small compared to the distances involved may also be considered point sources, as may capsule neutron sources.) The inverse square law states that radiation intensity from a point varies inversely as the square of the distance from the source. This can be expressed mathematically as: $I_1 \div I_2 = (R_2)^2 \div (R_1)^2$.

Here I_1 is the radiation intensity at distance R_1 from the source and I_2 is the radiation intensity at distance R_2 from the source. This formula shows that doubling the distance from the source decreases intensity by a factor of four; increasing the distance by a factor of three reduces the radiation intensity to one-ninth of its value, etc. The inverse square law does not apply to extended sources or radiation fields due to multiple sources.

B. Shielding

Shielding is one of the most important methods for radiation protection. To apply shielding methods, one must understand how x and gamma radiation is attenuated in an absorbing medium. Energy is lost by three methods: photoelectric effect, Compton effect, and pair production. The predominating mechanism depends upon the energy of the radiation and the absorbing material. The photoelectric effect is most important at low energies, the Compton effect at intermediate energies, and pair production at high energies. The last cannot occur unless the incident radiation has more than 1.02 MeV of energy. As x- and gamma-ray photons travel through an absorber, their decrease in number caused by these absorption processes is governed by the energy of radiation, the specific absorber medium, and the thickness of the absorber transversed. Mathematically, this may be expressed as:

$$\frac{\Delta I}{I_O} = -\mu \Delta x$$

where:

ΔI = reduction of radiation intensity

I_O = incident radiation intensity

μ = proportionality constant

Δx = thickness of absorber transversed

This equation can be solved by integration:

$$I = I_O e^{-\mu x}.$$

Here e is the natural logarithm base and I is the radiation intensity after absorption by material of thickness x. Using this formula, it is easy to calculate the radiation intensity behind a shield of thickness x, or to calculate the absorber thickness necessary to reduce radiation intensity to a desired level, if the factor μ is known. This factor is called the "linear absorption coefficient" when x is a "linear dimension." However, the value of μ depends upon the energy of the radiation and the absorbing medium. Tables and graphs in the Radiological Health Handbook give values of mass attenuation coefficients determined experimentally for all radiation energies and for many absorbing materials. To obtain μ, multiply the mass attenuation coefficient of the shielding material by its density. The larger the value of μ the greater the reduction in intensity for a given thickness of material. The fact that lead has a high μ for x and gamma radiation is partially responsible for its wide use as a shielding material. Figure 1 shows the relative shielding properties of some common materials.

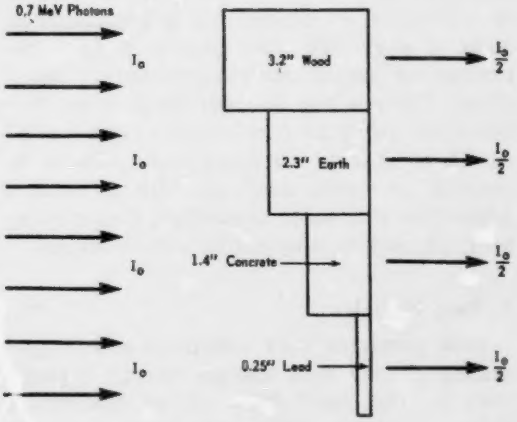

Figure 1.--Half Value Layers for Shielding with some Common Materials

If the radiation being attenuated does not meet narrow beam conditions, and/or thick absorbers are involved, the absorption equation becomes: $I = bI_0e^{-\mu x}$.

Here b is the buildup factor and takes into account increasing radiation intensity from scattered radiation within the absorber. Graphs of buildup factors can be found in the Radiological Health Handbook.

In discussing shielding, there are a few facts to keep in mind:

1. Persons outside the "shadow" cast by the shield are not necessarily protected.
2. A wall or partition is not necessarily a safe shield for persons on the other side.
3. In effect, radiation can "bounce around corners"; i.e., it can be scattered.

The third fact is so important that it merits further discussion. Scattered radiation is present to some extent whenever an absorbing medium is in the path of radiation. The absorber acts as a new source of radiation. Frequently, room walls, floor, and other solid objects are near enough to a source of radiation to make scatter appreciable. When a point source is used under these conditions, the inverse square law is no longer completely valid for computing radiation intensity at a distance. Measurement of the radiation is then necessary to determine the potential exposure at any point.

Shielding will attenuate beta radiation, and it takes relatively little shielding to absorb it completely. Therefore, the general practice is to use enough shielding for complete absorption. For low-energy beta emitters in solution, the glass container generally gives complete protection. In many cases, plastic shielding is effective and convenient. The absorption of higher-energy beta radiation may result in the production of electromagnetic radiation called bremsstrahlung, literally "breaking radiation." This is produced by deceleration of the beta particles when they interact with the shielding material. Electromagnetic radiation is more penetrating than the beta radiation that produced it and must be considered in shielding calculations. Principles used for attenuating x and gamma radiation from conventional sources should be used for shielding against this additional radiation. Since bremsstrahlung is most readily produced when high-energy beta particles interact with high atomic number materials (e.g. lead), this is a compelling reason for the use of glass, plastic, or other low atomic number materials for shielding against beta radiation.

Tables or graphs in the Radiological Health Handbook list the maximum range of beta particles of various energies in different absorbing media. These can be used to calculate the necessary shielding.

Fast neutrons are poorly absorbed by most materials; therefore, they must be slowed down for efficient absorption. Since the greatest transfer of energy takes place in collisions between particles of equal mass, hydrogenous materials are most effective for slowing down fast neutrons. Water, paraffin, and concrete are all rich in hydrogen, and thus important in neutron shielding. Once the neutrons have been reduced in energy, they may be absorbed by either boron or cadmium. When a boron atom captures a neutron, it emits an alpha particle. But because of the extremely short range of alpha particles, there is no additional hazard. Neutron capture by cadmium results in the emission of gamma radiation. Lead or a similar gamma absorber must be used as a shield against these gammas. A complete shield for a capsule-type neutron source may consist of: (1) a thick layer of paraffin to slow down the neutrons, (2) a surrounding layer of cadmium to absorb the slow neutrons, and (3) an outer layer of lead to absorb both the gammas produced in the cadmium and those emanating from the capsule.

C. Exposure Time

It may occasionally be necessary for a radiation worker to perform in areas of high exposure rates. This can be accomplished within the recommendations of the Federal Radiation Council or the National Council on Radiation Protection and Measurements if the total accumulated whole-body dose, within a period of 13 weeks, does not exceed 3 rems and if the average overall accumulated dose does not exceed 5(N-18) rems.(1) To stay within this limit, it may be necessary to work men in relays so that the RPG or MPD is not exceeded by any one man.

IV. INTERNAL RADIATION HAZARDS

A. Modes of Exposure

Radioactive materials may enter the body by ingestion, by inhalation of air containing radioactive materials, by absorption of a solution of radioactive materials through the skin, or by absorption of radioactive material (into the blood stream) through a cut or break in the skin. The danger of ingestion of radioactive materials is not necessarily that of a large amount swallowed at one time, but rather the accumulation of small amounts on hands, cigarettes, food, or other objects, thus bringing the material into the mouth frequently.

B. Sources

Any radioactive material that enters the body is an internal hazard. The extent of the hazard depends upon the type of radiation emitted and its energy, the physical and biological half-life of the material, and the radiosensitivity of the organ where the isotope localizes. Alpha and beta emitters present the most dangerous internal hazard because their specific ionization is very high. (The number of ion pairs formed per centimeter of path in any given medium is called the specific ionization for that particular ionizing radiation.) Polonium is an example of a potentially very serious internal hazard. It emits a highly ionizing alpha particle of 5.3 MeV energy, has a half-life of 138 days, and "creeps" out of containers. Tables in the National Bureau of Standards Handbook 69 list the physical and biological information necessary to evaluate the hazard of most radionuclides.

V. CONTROL OF INTERNAL RADIATION HAZARDS

Contamination prevention and control are the most effective ways to reduce internal hazards. Protective devices and good handling techniques are helpful in this respect. Dust should be kept to a minimum by the elimination of dry sweeping and the use of air filters. Laboratory operations with radioactive materials should be performed in hoods designed to keep room air contamination at a minimum. The exhaust air must be filtered and, if necessary, washed to eliminate any possible public hazard. Protective clothing should be worn so permanent clothing does not become contaminated. These all help limit the spread of contamination.

To prevent inhalation of radioactive materials, respirators should be available for emergency use in areas where the concentration of airborne activity is above maximum permissible levels. Eating and smoking in areas where radioactive materials are handled should be prohibited to reduce the ingestion hazard. Laboratory design and construction should be such that if decontamination becomes necessary, it is easily accomplished. It may be desirable to coat floor, walls, ceilings, and furniture with a strippable material for easy removal and disposal of contamination.

The proper instruments for handling radionuclides should be used to reduce the probability of accidents. There are many more fine points which should be considered for safe handling of radionuclides. Most are discussed in books and booklets (2-4) concerning this topic. Thorough study of such publications should be made before handling radionuclides. Proper planning of operations will eliminate many sources of hazards.

VI. SUMMARY

Time, distance, and shielding are the basic methods for radiation protection against external sources. The application of some combination of these methods will reduce radiation exposure to an acceptable level. The prevention and control of contamination, the use of protective devices, and good techniques should keep internal hazards below the maximum permissible levels.

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This material was prepared by Mr. Kenneth Eger, formerly of the Division of Radiological Health.

Sealed Sources

I. INTRODUCTION

The growing use of radionuclides in industrial, medical, and educational installations makes problems of preparation, handling, and storage increasingly more complex. For many uses, the radioactive material may be sealed by the manufacturer into containers especially constructed so that the radionuclide need not be removed for use, thus minimizing the dangers of contamination. Sources of this type are called "sealed sources".

II SURVEY OF SEALED SOURCE APPLICATIONS

A. Gamma Ray Sources

Large sources of gamma radiation are used in teletherapy, radiography, and instrument calibration. The most often used gamma emitting radionuclides are radium-226, cobalt-60, and cesium-137. The activity needed for radiography and calibration ranges from 50 to 50,000 millicuries, depending on use. Kilocurie activities are common in teletherapy.

Smaller sources are used in bin level and density gauges with activities of 10 to 1500 millicuries. Useful nuclides for these gauges include cesium and cobalt. Seeds and needles used in the treatment of pathological tissue range in activity from 1 to 20 millicuries. They usually contain radium, cobalt, radon-222, or gold-198.

Needles are constructed of platinum or stainless steel and are filled with the radioisotope either directly or with platinum cells in which the isotope has been previously placed as is illustrated in Figure 1. Seeds are prepared by sealing the active material in inactive metal tubing about three millimeters in length. Gold is often used as the tubing material. Other source containers are in the form of cylindrical capsules. The ends are usually secured by some combination of screw type plugs, welded or silver soldered caps. An example is given in Figure 2. All gamma ray sources are designed to absorb associated alpha and beta radiation.

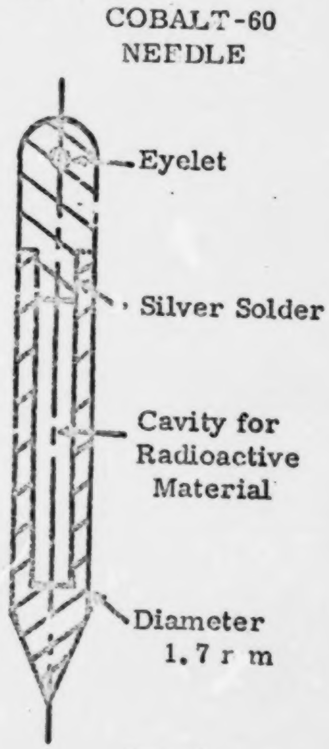
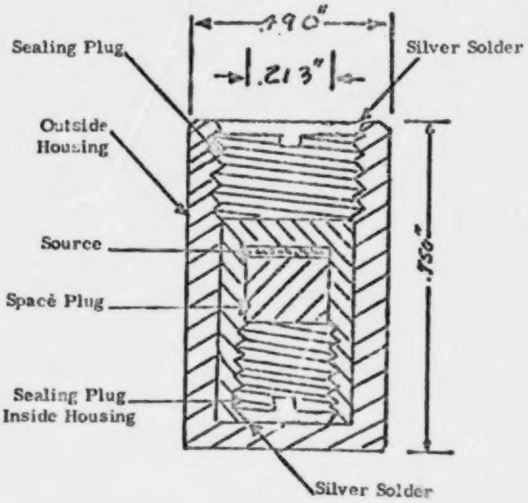


Figure 1

GAMMA TYPE
SEALED SOURCE



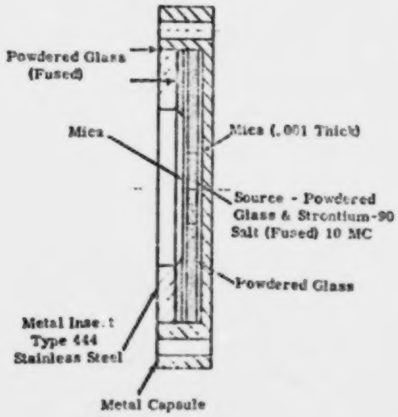
.190"
.213"
Sealing Plug
Silver Solder
Outside Housing
Source
Space Plug
.750"
Sealing Plug Inside Housing
Silver Solder

Figure 2

B. Beta particle sources containing strontium-90 are used in thickness gauges and have activities of 10 to 300 millicuries. The source is prepared by placing a fused mixture of a salt of strontium-90 in glass in a metal container. The beta particles are emitted through a mica window in the container. See Figure 3.

Sources of beta particles are used in medical application and are shaped according to the tissue to be irradiated. The eye applicator in Figure 4 consists of a spherical cap of silver backed strontium-90 foil imbedded in a plastic shell. It has an activity of two millicuries.

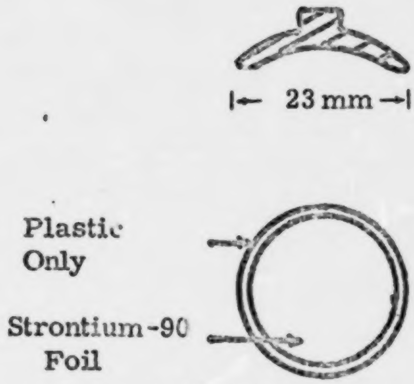
BETA-RAY SOURCE HOLDER
BACKSCATTER GAUGE



Powdered Glass (Fused)
Mica
Mica (.001 Thick)
Source - Powdered Glass & Strontium-90 Salt (Fused) 10 MC
Powdered Glass
Metal Insert Type 444 Stainless Steel
Metal Capsule

Figure 3

BETA PARTICLE
EYE APPLICATOR



23 mm
Plastic Only
Strontium-90 Foil

Figure 4

C. Alpha Particle Sources

Alpha particle sources are used in fire detection devices, vacuum gauges, and in static eliminators. Radium is used with an activity from 10 to 400 microcuries. These sources are in reality only "semi-sealed" since gaseous daughter products leave the source along with the alpha particles. The source for the static eliminator is a radium-impregnated gold foil with a thin coating of palladium.

D. Neutron Sources

Neutron sources consist of mixtures of radium or polonium and beryllium sealed in cylindrical monel cans. They are presented in detail in other lectures.

E. Visible Light Sources

Lamps with 200 millicuries of krypton-85 gas contained in a phosphor coated bulb are used as railroad switch lamps. Another example of this type of source is the familiar self-luminous dial (really "semi-sealed") found on watches and instruments. The source is a mixture of radium and a phosphor which is bound to the dial face.

III. CHARACTERISTICS OF THE RADIONUCLIDE AND ITS CONTAINER

A. Selecting a Radionuclide

The radionuclide or its compound selected for use as a sealed source should exhibit as many of the following characteristics as possible. It should:

1. Emit the desired radiation with the desired energy.
2. Be noncorrosive to its container.
3. Have a long half-life.
4. Be relatively easy to obtain.
5. Have high stability under irradiation.
6. Be free of water and organic compounds due to their subsequent decomposition into gases under radiation. This causes a dangerous pressure build-up*.
7. Show little danger of dispersion or ingestion in cases of source leak.
8. Be relatively easy to prepare for use.

For many uses, cobalt is taking over the traditional leadership of radium because of its greater safety. This safety is due chiefly to its use in the pure, solid, metallic form, its freedom from gaseous decay products, and the fact that it may be machined before activation.

B. Selecting a Container

The container must be chosen to suit its use and the nuclide it is to contain. The following points should be considered. It should:

1. Offer little resistance to the desired radiation while absorbing that which is unwanted.
2. Hold the radioactive material along with any radioactive decay products. This often means being gasproof.
3. Be resistant to internal pressure and chemical attack.
4. Be resistant to external wear, temperature and pressure extremes, and chemical exposure during shipment, use, and storage.
5. Be non-deteriorating with age and irradiation.
6. Have a shape and size to speed its handling.
7. Be easily marked as to its contents for identification from a distance.

Noble metals have the needed corrosion resistance and the high density for shielding but lack structural qualities. For this reason, stainless steels are replacing them. Because plastics tend to harden and crack under irradiation, they are unsuitable for other than very small sources. Glass is not recommended for use in any source.

IV. PRECAUTIONS DURING MANUFACTURE, USE AND STORAGE

A. Testing of Sealed Sources by the Manufacturer

The manufacturer of sealed sources must check the source for contamination after it has been placed in its container, sealed, and scrubbed clean. If an outer container is also used, the check must be made again. A source passing the above tests with the outside of each container showing a level of activity below 0.05 microcuries must be stored 30 days and then pass a leak test before being used or delivered. In addition, sources for medical use must be calibrated as to dose rate.

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*Radium and cesium sources must not be heat sterilized because of this danger.

B. Handling and Using Sealed Sources

Handling of sealed sources may be completed with less exposure time than with other sources. This is because fewer complex operations like pouring and measuring are needed to ready the source for use. Common causes of excessive irradiation of personnel engaged in handling sealed sources are:

1. Lack of correct tools.
2. Exposure to more sources than necessary.
3. Cumbersome shielding which serves no purpose, such as lead-rubber gloves and aprons.
4. Ill-fitting applicators, needle eyes not large enough for easy threading, and cavities in applicators too small for the easy insertion and removal of source capsule.(2)

A number of tools have been specially designed to handle sealed sources. These either reduce exposure time or increase the distance of the technician from the source. For example, automatic radium dispensers are used to remove radium tubes from storage and load them into applicators. Its operation is similar to that of a chewing gum dispenser and permits the operator to do his work by the pull of a lever well away from and well shielded from the activity. Other devices in use are:

1. Forceps with adjustable "spring-jaws" to prevent excessive pressure on the source.
2. Clamping vices and chucks.
3. Devices for threading needles and tubes.
4. Magnetic and pneumatic holding and moving devices.
5. Electromechanical "slaves" for remote operations.

Some cautions in handling should be noted: Tools should be chosen carefully. A seemingly helpful pneumatic device used with a calibration source raised the source into a tube above its shield with a stream of air. The source was held up by the air during use and returned to the shield by turning the air off. The wear on the capsule while moving in the tube and potential damage on dropping presented a hazard greater than if the operator had removed the source with tongs.

All tools should be used in conjunction with sufficient portable or permanent shielding.

Practice runs with dummy sources should be made whenever a new operation is begun. Some applicator sources are shipped by the manufacturer with dummy sources included for this purpose.

C. Storing Sealed Sources

During storage as well as use, sealed sources must be continually tested for leakage. If leakage is found, spread of contamination must be prevented and the source supplier and the AEC should be consulted for specific instructions.

Storage containers should be designed to provide generous shielding protection for employees. In this way radiation doses unavoidably received during application of the sources can be somewhat compensated for.

One person should be designated custodian and charged with the responsibility of security and control of stored sources to prevent their loss.

V. SUMMARY

Over-exposure is a danger wherever there are radiation sources, however, sealed sources present a special danger to personnel who may judge their potency by the innocence of their containers. Education of personnel, adequate marking and shielding, and constant leak testing are the means of safety. With these precautions, properly designed sealed sources represent a useful method of managing radioactive material and can mean a considerable reduction in radiation hazards for personnel.

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Sealed Sources in Medicine

I. INTRODUCTION

Radioactive material is used in medicine for many purposes and in several forms. The relative hazard involved in using a particular source depends not only on its form, but the quantity and the type of radiation emitted. Other factors being equal, radioactive materials which are tightly and permanently sealed are less dangerous than liquids or dry preparations which can be accidentally split and spread over a large area.

Sealed radioactive sources are used extensively in the medical field. The sealed sources used in medicine can be divided into two broad categories.

A. Those which are applied as non-collimated sources and placed within or close to the tissue being treated.

B. Those in which the radiation is collimated and directed at the tissue being treated.

II. NON-COLLIMATED SOURCES

The various types of non-collimated sources can be divided into three major subdivisions; (1) interstitial, (2) intercavitary, and (3) surface applications.

A. Interstitial

The interstitial use of sealed sources involves actually implanting the sealed source into the tumor or soft tissue to be treated.

1. Permanent Implants

a. Radon seeds

Radon is obtained from radium in a radon plant where a radium salt in solution is kept in a shielded vacuum-tight vessel. Periodically the radon gas, which is produced as the radium disintegrates, is pumped off and then forced into hollow gold tubing and sealed off into tiny seeds. These are placed in the tumor in a predetermined pattern to give the desired dose. Radon has a half-life of only 3.83 days. The major gamma activity disappears after about one month and since gold is nonreactive and relatively innocuous, it can be left in the body permanently. In the past there have been a number of radon plants, but they are gradually being closed and dismantled through lack of demand.

b. Gold seeds

Gold-198 has largely taken the place of radon seeds. Gold is very easily activated by thermal neutrons. Its half-life is 2.7 days and emits a monoenergetic gamma ray of 0.412 Mev and beta radiation of .96 MeV. The gold seeds are implanted into tissue by a pistol type device which actually injects a seed into the tissue.

2. Temporary Implants

a. Radium needles

Radium needles have been used for many years as temporary implants in the treatment of tumors. The radium needles are inserted into the tumor and surrounding tissues in a predetermined pattern designed to give the desired dose distribution to the tumor.

b. Cobalt-60 needles

The Cobalt-60, usually in the form of a wire, is placed inside a sheath of stainless steel or platinum-iridium and used in the same way as radium.

B. Intercavitary

In this type of application the source is placed into any organ of the body which is hollow.

The rectum, the uterus, and certain other organs into which something can be inserted are frequently treated in this way.

C. Surface Applications

In this application the skin is treated by applying a plaque of some kind to the malignant tissue.

III. COLLIMATED SOURCES

The use of high intensity gamma sources for treating deep-seated tumors was started in the 1920's and has become known as Teletherapy.

A. Teletherapy Units

Until the summer of 1951, all radiation therapy units used radium. These units usually contained four to ten grams of radium.(1) The availability of the much cheaper cobalt-60 sources of high specific activity has stimulated interest in teletherapy and today cobalt-60 units are to be found in all parts of the world. Cesium-137 is also used on a limited scale today and shows promise of increased use in the future.

IV. SUMMARY

Along with the increased uses of non-sealed sources in medicine today, sealed sources are seeing increased uses. Sealed sources can be handled carefully by experienced personnel with a minimum of exposure.

One of the major potential hazards is that the small innocent looking sealed sources may become lost and/or fall into the hands of a person who is not aware of their potential hazard.

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This material was prepared by Dr. H. F. Stewart of the National Center
for Radiological Health.

Sealed Sources in Industry

I. INTRODUCTION

Sealed radioactive sources have had accelerated use in industry in recent years for many different purposes. They have provided industry with improved methods for process and quality control and the opportunity for the automation for some processes. The principal uses for sealed sources in heavy industry are for radiography, density gauging, bin level control, thickness gauging, liquid level control, fire detection, and railroad switch lamps. The principal radionuclides used in these sources are shown in Table 1. Of particular interest to those in radionuclide protection programs are the columns entitled Half-Life, Principal Energy and Approximate Gamma Ray Exposure. The data in these columns provide information which is useful in evaluating the relative hazard level inherent in the use of these sources.

Radium, a natural radionuclide, is included. While the advent of pile-produced radionuclides have largely displaced radium for radiography, it, nevertheless, is still used in this application. In addition, small (microcurie) radium sources are being used in new applications such as fire detection and vacuum gauging. Its use in radiography, generally, presents a greater potential radiation exposure of personnel than usually found in pile-produced sources. This is due to the fact that the latter type of radionuclides are more often installed in the shielded camera type of radiography equipment, while radium is largely used in "fish pole" radiography techniques. The intense energy (hard gamma) of Cobalt-60 provides this radionuclide an advantage in its use for radiography and bin level detection of dense materials. Cesium-137, due to its relatively long half-life and strong gamma ray emission, is becoming a principal source material for density gauging of slurries and even more dense mixtures. The short half-life of Iridium-192 limits its application as a source material for industrial sources, but this radionuclide has some use in radiography. Where a short-term application for radiography of light alloys or thin sections of metals is involved, the use of Iridium may have advantages. From the industrial and health physics point of view, the short half-life is a favorable factor in terms of storage time and disposal problems. In about a year, an Iridium source will have decayed to about 5 half-lives and, therefore, a 500 millicurie source decays to about 16 millicuries within this period. Krypton-85, a gaseous source, has had some use in sealed sources. It has been employed in thickness gauges and is being used in railroad switch lamps to replace the common electric lamp. Its gaseous stage gives it, an advantage as a source as there is little, if any, contamination problem in the event of breakage under normal ventilation conditions, with the possible exception of an extremely confined space. Strontium-90 as a source material is limited to coating thickness gauging and thickness gauging of light materials, such as paper or plastics, since it is a pure beta emitter. In this application,

TABLE 1--Principal Isotopes in Sealed Sources

Isotope	Physical Form	Types of Use	Half Life	Principal energy		Approx. Gamma ray exposure rate/curie
				Type	Mev	r/hr./ft.
Ra-226	Solid	Radiography Fire Alarm Vacuum Gage	1620y	Gamma Alpha	0.2 -	9.14(1) -
Cs-137	Solid	Density Gage	33y	Gamma	0.66	4.25
Co-60	Solid	Radiography Bin Level	5.3y	Gamma	1.17, 1.33	14.4
Ir-192	Solid	Radiography	75d	Gamma	0.3, 0.5	3.24
Kr-85	Gas	Thickness Gage Switch Lamp	10y	Gamma Beta	0.54	0.021
Sr-90	Solid	Thickness Gage	28y	Beta	Bremsstrahlung	-

(1) - Assuming encapsulation in 0.5 mm platinum

the Bremsstrahlung radiation, produced when beta particles lose energy by the radioactive collision process is used. This type of process is basically the production of x-rays. Bremsstrahlung is produced when fast moving electrons collide with the electric field of nuclei of high atomic number in the shielding material of the source capsule. In view of the fact that strontium and radium are so-called bone seekers, once they enter the body, any rupture of these sources by shock or other means adds to the radiation hazard potential of these radionuclides.

II. SEALED SOURCE APPLICATIONS

Probably the major application of sealed sources in industry has been their application to process and quality control. Such applications as controlling density of slurries, bin and tank level control, and sheet and coating thickness control have steadily advanced over the past few years. In all instances, the general principle is the same to the extent that the primary beam radiation of gamma rays or x-rays from Bremsstrahlung radiation is detected by a counter (photographic film in the case of radiography) after passing through, or reflecting back from, the material to be measured or controlled.

One may therefore, describe the industrial applications of sealed sources by the property of radiation which is utilized. Therefore, industrial applications are based upon the following characteristics of radiation

	CHARACTERISTICS OF THE RADIATION USED	EXAMPLE
1	Ability to penetrate material	thickness gauge
2	Reflection from surface	density thickness gauge
3	Ability to produce ionization	static elimination
4	Ability to cause certain materials to luminesce	light sources

A. Gauges Using Penetration Principle

1. THICKNESS GAUGES

The ability of radiation to penetrate matter is the principle upon which the widest use of sealed sources in industry is based. This principle, upon which the transmission type of thickness gauges operates, is applied to the non-contact method of gauging and thus produces a more uniform sheet of steel and metals, rubber, glass and many other sheet materials. The sheet to be gauged passes between a source and radiation detector which, in turn, is connected to an amplifier and recording device. The electric signal caused by the detection of the transmitted radiation can be applied to automating the production process. Figure 1 reveals a thickness gauging of one supplier designed for use in the heavy metals industry.

Another type of gauge utilizing the penetrating of transmitted radiation is the pipe wall thickness gauge. A small radium source is utilized from which the gamma radiation is employed and detected, as it passes through the pipe, by a detector located in the handle.

2. DENSITY GAUGE

The density gauge also operates upon the penetration principle that if the size or thickness of material remains constant, the transmitted radiation can be used to measure density. This can be applied to measuring or controlling the amount of solids in slurries. In this application, changes in the mass per unit volume will change the amount of radiation absorbed, thus providing a basic measure of density, percent of solids or specific gravity.

3. LEVEL GAUGE

The tank or bind level gauge is still another application of the penetrating radiation to gauging applications. Generally, the source and detector are mounted on opposite sides of the tank or bin. As the level of fluid or solids rises and intercepts the radiation beam, the intensity of the beam is reduced. This principle can be used for high and low level control of liquids or solids in tanks or bins and has been adapted to measuring and controlling the height of molten metal in a cupola. Gamma emitting sources are generally the source of choice in these gauges. Figure 2 is a bin or tank level control application. High and low level control can be achieved by a single or by two separate gauges. When a single source is used, a long radiation detector is utilized with a wide beam emitting source design. Level is controlled within the height of the detector.

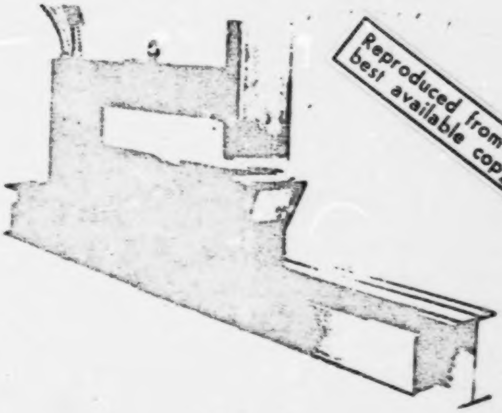

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Figure 1

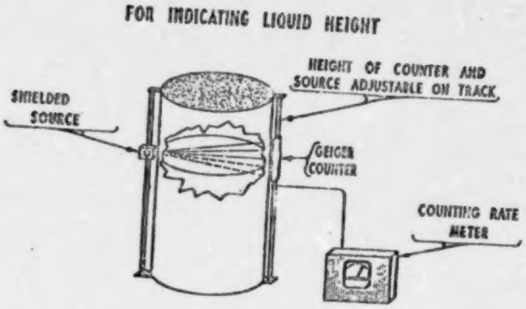
FOR INDICATING LIQUID HEIGHT
SHIELDED SOURCE
HEIGHT OF COUNTER AND SOURCE ADJUSTABLE ON TRACK
GEIGER COUNTER
COUNTING RATE METER

Figure 2

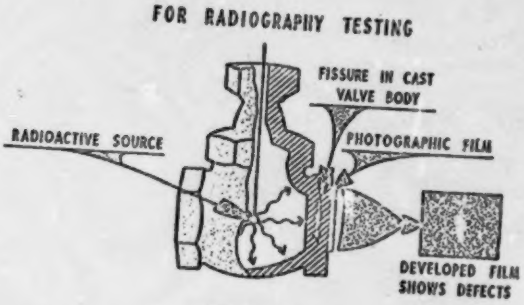
FOR RADIOGRAPHY TESTING
FISSURE IN CAST VALVE BODY
RADIOACTIVE SOURCE
PHOTOGRAPHIC FILM
DEVELOPED FILM SHOWS DEFECTS

Figure 3

B. Radiography

Sealed sources applied to radiography are based upon utilization of the penetrating ability of radiation. These sources may be built into a shielded camera, a manually operated mechanical "snaking" arrangement, or may be used unshielded with the old "fish-pole" technique. Gamma emitting sources are the principal type of source utilized. While Radium and Cobalt-60 are the principal radionuclides, others which have some application are Iridium-192, Thallium-170, Sodium-24, Cesium-137 and Tantalum-182. The "fish-pole" application is shown in Figure 3. In this technique the source is positioned in the open for radiographing several specimens by the panoramic exposure technique. Figure 4 reveals the shielded camera type of radiographic equipment. The source is fixed in the camera and is not removed when making a film exposure, instead a shutter is open allowing the radiation to be used. This is one of the best protected radiographic applications although there still remains a major personnel exposure problem. Figure 5 shows the equipment used in the "snaking" technique. In this equipment, a portable shielded source holder secures the source when not in use. The source is mechanically withdrawn and returned through a flexible tube for radiographic applications. Once the source is withdrawn from the holder, the radiation protection problem is of about the same magnitude and scope as in the application of an unshielded source.

C. Gauges Using the Reflection Principle

The major sealed source application utilizing the reflection principle is in the backscatter type of gauge used to measure coating thickness. This is useful in industry in the accurate measurement of the thickness

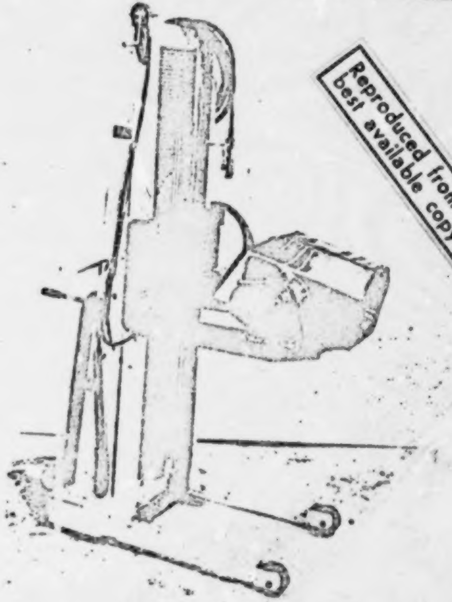

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Figure .

National Center for Radiolo

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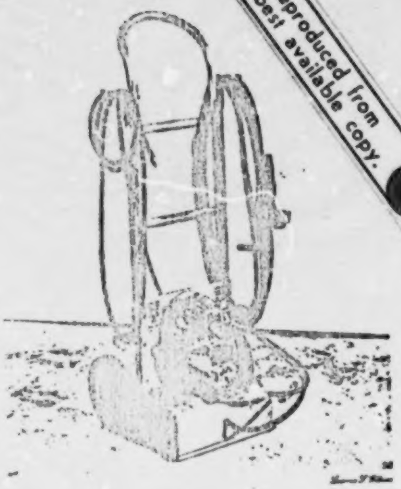


Figure 5

of coatings laid over a base metal, such as steel. In this type of gauge, a beta-emitting source is used. The change in the intensity of reflected radiation from the uncoated and coated metal is proportional to the thickness of coating up to a certain limiting value. This type of gauge can be used to automate the coating process. Figure 6 illustrates the backscatter principle as applied to a coating thickness gauge. The thickness of some coatings is also measured by the transmission type of gauge.

Other gauges utilizing the reflection principle are used in determining the density and moisture content of soils. The principle of these applications is shown in Figure 7.

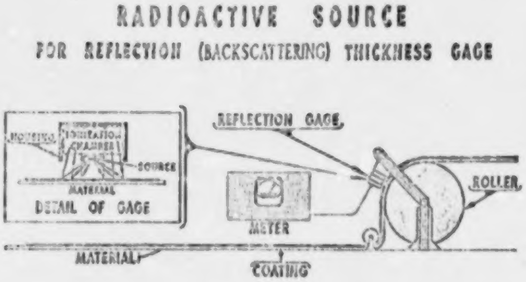

RADIOACTIVE SOURCE
FOR REFLECTION (BACKSCATTERING) THICKNESS GAGE
HOUSING
IONIZATION CHAMBER
SOURCE
MATERIAL
DETAIL OF GAGE
REFLECTION GAGE
METER
ROLLER
MATERIAL
COATING

Figure 6

A probe is utilized which houses a source and detector. The probe is inserted through a steel tube driven into the ground. The soil probe employs a Cesium-137 or a Cobalt-60 source. The gamma rays are scattered by the soil surrounding the tube. Some of this radiation is reflected back to a detector, shielded from the primary radiation, which is mounted in the top of the probe. The amount of reflected radiation is a function of the soil density recorded in pounds per cubic foot. The moisture probe uses a neutron source, activated by alpha or gamma rays, for neutrons are strongly affected by the hydrogen atoms; they are slowed down and after several such collisions, some are reflected back to the vicinity of the probe. The top of the probe contains a detector surrounded by silver foil and is shielded against the primary radiation from the neutron source. When a reflected slow neutron strikes the foil, a short-lived radionuclide of silver is formed. The radiation from this rapidly decaying radionuclide is measured by the counter which is insensitive to the neutrons. This measurement can be related to the moisture content of the soil.

D. Gauges Using Ionization Principle

1. The ability of radiation to ionize gases, particularly air, is widely used in gauges. These are vacuum and fire detection gauges and static eliminators.

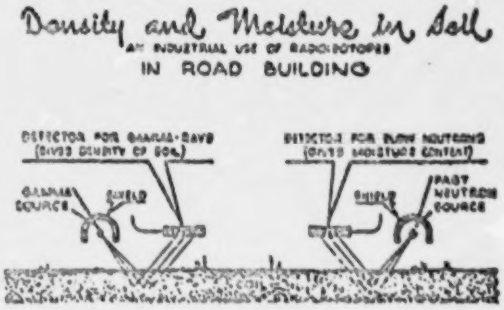
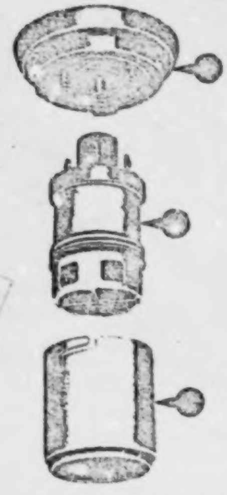

Density and Moisture in Soil
AN INDUSTRIAL USE OF RADIOISOTOPES
IN ROAD BUILDING
DETECTOR FOR GAMMA-RAYS
(GIVES DENSITY OF SOIL)
GAMMA SOURCE
SHIELD
DETECTOR FOR SLOW NEUTRONS
(GIVES MOISTURE CONTENT)
SHIELD
FAST NEUTRON SOURCE
SOIL

Figure 7

RADIOACTIVE FIRE DETECTOR



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PYR-A-LARM DETECTOR HEAD

A. Molded phenolic socket base.
B. Plug in detector assembly.
C. Anodized aluminum locking shell.

Detector measures 5¾" in length and 4½" overall diameter at base which mounts on a standard 4" round junction box. It is [illegible] and functional in design.

Figure 8

a. Fire Detection Gauge

In the fire detection gauge the sensing element uses a small radium source. The assembly of this device is shown in Figure 8. The detector utilizes the ionization principle in which air is made conductive by means of the alpha particle radiation. A voltage applied across an ionization chamber produces a flow of electric current by the movement of the ions and electrons from dissociation of air molecules. The current depends upon the number, size and weight of molecules present in the ionization chamber. Products of combustion affect the current to a greater degree than other gases because combustion gases contain large particles.

b. Static Eliminators

Static electricity is a major problem in many industries such as paper, printing and textiles and occurs whenever the products manufactured possess insulating properties. Radioactive static eliminators utilize the alpha particle radiation from small radium or polonium sources. Through the ability of alpha radiation to ionize air, the static charges can be removed at selected points along the moving stock by electrical grounding. Figure 9 indicates a polonium static eliminator bar.

While radium and polonium emit strong alpha particles and both are effective static eliminators, polonium is preferable for several reasons. Polonium is an ideal static eliminator because it emits more energetic alpha radiation, has high specific activity and its decay product is the stable element lead. Radium also emits gamma rays and beta particles and therefore requires more radiation protection than the weak gamma emitting polonium.

E. Utilization of Ability to Cause Luminescence

An application of the luminescence principle for application of sealed sources in industry is of fairly recent development. This is the development of a lamp using Krypton-85 as a portable lamp and as a fixed railroad switch lamp. In this application, the light source consists of a phosphor-coated bulb filled with radioactive krypton gas. The lamp may be permanently fixed

Alphatron-Polonium Static Eliminator
RADIOACTIVE
Wear Gloves for Installation and Handling
Canadian Radium & Uranium Corporation,
New York 20, N.Y.

Figure 9

along the track for a switch signal or may be portable. These lamp units weigh from 20-55 pounds.

III. SOURCE DESIGN FACTORS AND RADIATION EXPOSURE

The design of the source capsule and the source holder and the type of its assembly in the gauge or housing are of paramount importance in radiation protection. Herein lies the core of a radiation protection program for sealed sources. If the source is properly designed for use in heavy industry and the environment therein, the radiation exposure potential will be reduced to a minimum. One of the first considerations therefore in considering safety is the source design. Requirements for a safe sealed source are listed below:

a. The radionuclide must be in a non-friable form, hermetically sealed in a source container.

b. The source container and source holder must be constructed of materials which will not deteriorate under influence of radiation, corrosion, vibration and shock.

c. The source container must be incorporated in a source holder in such a manner that removal of the source container by unauthorized personnel is highly impractical.

d. The source container and holder must be constructed in conformance with requirements of the U.S. Atomic Energy Commission.

e. The design of the gauge, machine or device must incorporate sufficient shielding to prevent radiation, other than primary beam radiation, in excess of a 6.0 - 7.0 milliroentgens per hour (mrh) emanating through the housing of the gauge, as measured on the surface of the housing.

In Handbook 66 of the National Bureau of Standards, entitled "Safe Design and Use of Industrial Beta Ray Sources", there is a wealth of valuable health physics information. While the above handbook pertains to beta ray sources, much of the basic considerations apply to any sealed source. For example, it is recommended that the source materials be in a stable physical and chemical form. This is very important in industry in order that the isotope remain intact under any chemical or physical influence to minimize the contamination problem. Such influence may be moisture, corrosive liquids or gases, vibration, shock, and temperature extremes. All such environmental factors must be carefully considered by the user and manufacturer. In addition, no source, gauge or device should be purchased unless test data on a prototype of each new design has indicated adequate physical and chemical stability and surface radiation measurements indicate adequate shielding by the housing.

BASIC PRINCIPLES OF NUCLEAR REACTORS

I. Introduction

On December 2, 1942, the world's first nuclear reactor went critical. This scientific achievement signaled the beginning of a new era: the atomic age. Utilizing the energy liberated from the heart of the atom, mankind's dream of an unlimited source of power was realized; his dependency on fossil fuel, a diminishing supply, was broken.

Scientific progress and technological advances in the design and construction of reactors have made the cost of producing electrical power by nuclear reactors competitive with production by conventional methods in many areas. Advances in reactor design coupled with declining resources of fossil fuels will undoubtedly result in even more extensive use of nuclear energy for electrical power generation in the future.

II. Fission

Fission is the process whereby an atomic nucleus splits, usually as a result of a neutron-induced interaction, into two lighter nuclei called "fission fragments." Simultaneously with the splitting, neutrons, gamma rays, and a quantity of energy are liberated. The amount of energy released per fissioning nucleus can be calculated from Einstein's formula, $E = mc^2$ (energy equals mass times the speed of light squared). The difference in mass of the fission products and that of the original atom is the "mass difference" which has been converted into energy during the fission process.

Since neutrons are uncharged particles, they are not affected by the coulomb field of the nucleus of an atom, and can enter the nucleus more readily than can charged particles. Therefore, neutrons serve as projectiles to add energy to the nucleus, upsetting its energy balance and causing fission. Two or three neutrons are released during the fission process. These can enter other fissionable nuclei, causing additional fissions - a "chain reaction."

Almost all (over 99 percent) the neutrons produced in the fissioning process are released within 10^{-14} seconds after fission occurs and are known as "prompt neutrons." About 0.64 percent of the neutrons produced are expelled from the fission products over a period of 0.05 to 55.6 seconds and are called "delayed neutrons."

Even though the delayed neutrons comprise a very small part of the neutrons released, they have an important bearing on the time-dependent behavior of reactors. However, in a discussion of the rudimentary principles of operation of a reactor, only the prompt neutrons need be considered.

These prompt neutrons, emitted in the fission process, range in energy from nearly zero to about 10 MeV, with the majority having energies of about 1 or 2 MeV.

There are several nuclides which are fissionable by neutrons of all energies Of these, only ^{235}U is both naturally occurring and sufficiently long-lived to be of practical value as a nuclear fuel. This fact alone makes uranium of prime interest for reactor use. However, ^{235}U constitutes only about 0.7 percent of natural uranium. Even so, ^{238}U, which constitutes over 99 percent of natural uranium and is not fissionable by slow neutrons, is important as the raw material for the production of ^{239}Pu. As will be discussed later, this fact is central to the concept of breeder reactors.

III. Reactor Theory

To achieve a self-sustaining nuclear reaction, or criticality, the following condition must prevail: The rate of neutron production must at least equal the rate of neutron losses. The isotope ^{235}U is primarily responsible for the fission process in a reactor. Uranium-238 will only fission with neutrons having energies greater than 1 MeV. Even then, the probability that a fast neutron will fission ^{238}U is relatively low. Fast fission of ^{238}U accounts for only a few percent of the total fissions.

All neutrons produced in the fission process are not available to sustain the process. Some diffuse away from the fuel region and are lost. Some that remain in the fuel region undergo non-fission capture by the fuel and the materials used for reactor construction.

Production and losses are illustrated by the neutron cycle in Figure 1. Upon the fissioning of ^{235}U, the fast neutrons released may cause ^{238}U atoms to fission, producing additional neutrons, or the fast neutrons may strike the moderator. The moderator reduces the neutrons' energy through elastic scattering to thermal or near thermal energies. At these energies they are most likely to cause further fissioning of ^{235}U.

To reduce the loss of neutrons escaping from the system, one can increase the size of the system. The minimum quantity of fissile material necessary to maintain a chain reaction is called the critical mass. The critical mass for a given reactor depends on a wide range of factors, although for a specific reactor design it always has a definite value.

The ratio of neutrons available for fissioning in any one generation to the number available in the immediately preceding generation is designated as the effective multiplication factor, "k_{eff}."

$$k_{eff} = \frac{\text{number of neutrons produced in one generation}}{\text{number of neutrons produced in preceding generation}}$$

For the chain reaction to be sustained in a steady state, k_{eff} must be equal to one. In this case the system is critical, and the number of neutrons available for further fissioning balances those lost through leakage or capture. When k_{eff} is less than one, the chain reaction is not maintained, and the system is sub-critical. More neutrons are lost than are being produced. For k_{eff} greater than one, a surplus of neutrons is being produced in each generation; the system is supercritical.

IV. Reactor Design

A. Core

The core consists principally of the fuel, moderator and structural material.

Because of design and operating difficulties inherent in fuels consisting of naturally-occurring uranium, enriched uranium - with a higher percentage of ^{235}U than the 0.72 percent occurring naturally - is used. The degree of enrichment depends on the design features of the reactor or vice versa. Enriched fuel has several advantages, including:

1. A wider variety of materials (coolant, moderator, construction material, etc.) is possible in the design of the reactor.

2. High fuel burn-up is achieved; that is, a larger percentage of the ^{235}U nuclei are fissioned, so the fuel can be more efficiently used.

3. Higher power densities (power output per core volume) can be obtained with enriched than with natural uranium.

The fuel is formed into rods or plates to improve heat removal. It is encased in a protective cladding which contains the fission products, prevents chemical reactions between fuel and moderator, and provides structural support.

Several physical factors should be considered for cladding materials: low neutron capture probability, structural strength at high temperatures, good heat transfer, and non-corrodible characteristics.

Commonly used cladding materials that meet these requirements are aluminum, zirconium, alloys of the two, and stainless steel.

B. Moderator and Reflector

Slow neutrons have a higher probability of producing fission in ^{235}U than fast neutrons. Since neutrons produced by fission have a wide spectrum of energies, a moderator is used to slow them down and enhance the fission process. On the average, neutrons lose more energy per elastic collision with particles of equal mass (i.e. hydrogen nuclei) than they do in colliding with heavier particles. For this reason, materials with low atomic weight - generally hydrogen or hydrogenous compounds - are used for moderators.

Because some of the neutrons are scattered at angles greater than 90 degrees (i.e. back in the general direction from which they came), moderating materials are also suitable as reflectors to reduce neutron leakage. Thus, material of low mass number interspersed among the fuel elements serves as a moderator and outside the reactor core serves as a reflector.

The reflector and moderator material should have a low probability for neutron capture. Materials most commonly used for reflectors and moderators are:

1. Water

   Because of its hydrogen content, water serves as a good moderator and reflector. Since water is also cheap, it is often used in reactors in a dual role as moderator-reflector and coolant. A disadvantage is its relatively low boiling point requiring expensive high pressure vessels and piping for high temperature operation. Also, since water has a relatively high thermal neutron absorption cross-section, the fuel in a water-moderated reactor must be enriched with ^{235}U to offset the additional neutron loss.

2. Heavy Water

   Of all the moderators in use, heavy water (^2H_2O) has the lowest neutron absorption to thermalizing ratio. It is a very good moderator and coolant, but high production and purity-maintenance costs limit its use.

3. Graphite

   Graphite is easily purified, machined, and relatively inexpensive. It also has a very low thermal neutron capture cross-section. Its brittleness causes difficulties when it is used as a structural material. Graphite also reacts with oxygen at high temperatures.

4. Beryllium and Beryllium Oxide

Both these materials are good moderators but are relatively expensive. Their disadvantages are that they are brittle and react with air or the moisture in air. They are also very toxic and, therefore, hazardous to fabricate. Beryllium and its oxide are only used in special applications.

When the arrangement of the core is such that the fuel and the moderator are separate entities, it is called a "heterogenous reactor " (schematically shown in figure 2). In a few operating reactors the fuel is intimately and uniformly mixed with the moderator. These are called "homogeneous reactors."

C. Coolant

The great quantities of heat produced in the reactor core must be removed to prevent the fuel elements from melting. For electricity production, the removed heat is used to produce steam to power generators. The cooling system removes the heat by circulating a heat-absorbing material through the core. The heat generated in the fuel elements is transferred to the coolant and circulated out of the core. The most commonly used coolants are:

1. Water and Heavy Water

These are both good coolants and good moderators. The chief disadvantages are water's corrosiveness and its low boiling point.

Pressurized water reactors solve the latter problem by keeping the water under high pressure, thereby raising its boiling point. Boiling water reactors - although pressurized - allow the water to boil, forming steam.

2. Gases

Air was used as the coolant in the early reactors. Now gas-cooled, high-power reactors use gases other than air, because air reacts unfavorably with structural materials in the core. Helium and carbon dioxide have been successfully used as gas coolants. Gas cooling systems require expensive pumping arrangements unless the gas is kept under high pressure.

3. Liquid Metals

Liquid metals - particularly sodium and sodium-potassium - are used as coolants where neutron moderation is undesirable, as in fast reactors.

D. Shielding

Of the radiations emitted by fission fragments produced in the fuel elements, neutrons and gamma rays present the most serious shielding problems. Alpha and beta particles are generally absorbed by the fuel cladding and other materials used in reactor construction.

Since the probability of neutron capture (removal) increases as the neutron kinetic energy decreases, it is desirable first to moderate or slow the neutrons down and then remove them through capture reactions. Good neutron moderators are low-density materials with a high hydrogen content. Good absorbers for gamma rays are high-density materials, such as lead or iron. Concrete has proven a good compromise for shielding against both gamma rays and neutrons from reactors. It contains both low and fairly high atomic weight materials - hydrogen and silicon. In addition to good shielding properties, concrete has good structural qualities and is relatively inexpensive. Iron punchings and boron can be added to enhance gamma ray shielding and neutron capture respectively. Because of these assets, concrete is used as a shielding material in a majority of reactors.

Water is used as a shielding material in special applications. Although its shielding properties are good, water generally presents considerable construction difficulties.

E. Control and Safety

The operation of a reactor can be described in terms of the multiplication factor, k_{eff}. Control rods maintain the proper k_{eff} factor for various stages of reactor operation.

Control rods are made of materials which have a high probability of capturing neutrons, thus removing them from the core region and making them unavailable for further fissioning. The neutron population is controlled by moving the rods in or out of the core region. With precise positioning of these rods, the point where k_{eff} equals one is reached. A stable, critical condition then exists in the reactor.

Regulating or control rods are usually cadmium or boron-steel, positioned electrically and/or hydraulically. Control rods are classified as either coarse or shim rods. The names refer to their degree of adjustment. The former are used for making gross adjustments, while the shim rods are used for making finer adjustments in the number of fission events. Other rods, called safety or scram rods, are strategically positioned in the core. In the event of a drastic increase in k_{eff} - hence fissions - these rods are inserted in the core immediately to shut down the reactor. Control rods may also be used as safety rods.

A fairly new concept of reactor control is adding boron directly to the coolant. The concentration of boron in the coolant is varied for routine control with major reactivity changes controlled by rods.

V. Reactor Classification

Reactors are classified by many categories, such as fuel-moderator arrangement, type of coolant, reactor use, etc., or by a combination of these. Some of these categories are listed below:

A. Fuel-Moderator Arrangement

1. Homogeneous - fuel and moderator are in contact and intimately mixed with each other.

2. Heterogeneous - fuel lumped into rods surrounded by moderator.

B. Use

1. Research Reactors - a reactor primarily used for research; either as a prototype or proving ground for future reactor design or operated to produce neutrons for pure scientific research.

2. Power Reactors - heat produced in the core is removed by the coolant and put through various heat exchange systems where it is eventually converted to electrical or mechanical energy (boiling water and pressurized water power reactor systems are schematically shown in figure 3).

3. Isotope Production Reactors - high neutron fluxes produced in the reactor are used to produce radioisotopes.

4. Breeder Reactors - the ^{238}U present in the fuel is incorporated into the reactor design. Slow neutrons are absorbed by the ^{238}U nucleus and the following reactions occur:

$${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \xrightarrow{{}^{0}_{-1}\beta} {}^{239}_{93}Np \xrightarrow{{}^{0}_{-1}\beta} {}^{239}_{94}Pu$$

Plutonium-239, like uranium-235, is fissionable with thermal neutrons. In addition to producing energy which may be used for power generation, the breeder reactor produces more fissionable material than it consumes.

C. Neutron Energy

1. Thermal Reactors - use thermal energy neutrons to produce fission.

2. Fast Reactors - use high energy neutrons to produce fission.

3. Intermediate Reactors - use intermediate energy neutrons to produce fission.

D. Coolant

1. Boiling Water - system is pressurized, but controlled boiling is allowed in the core. Steam is removed via a steam separator.

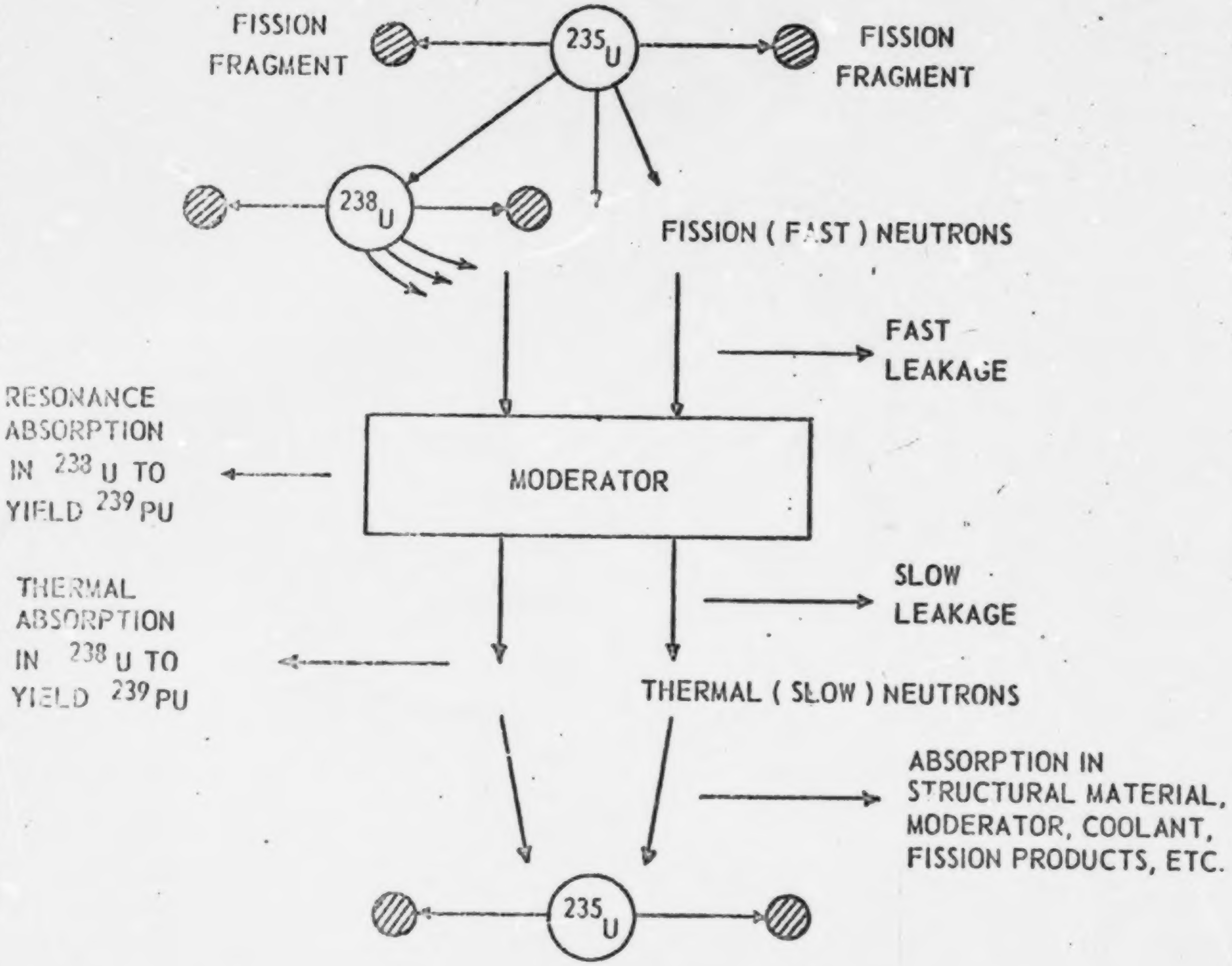
2. Heavy Water - deuterium oxide (D_2O) is used instead of ordinary water, H_2O.

3. Pressurized Water - coolant system is pressurized to the extent necessary to prevent boiling in the core. Steam is produced in a secondary system at lower pressures.

4. Liquid Metal - various liquid metals are used as coolants, primarily in fast reactors where no moderator is wanted.

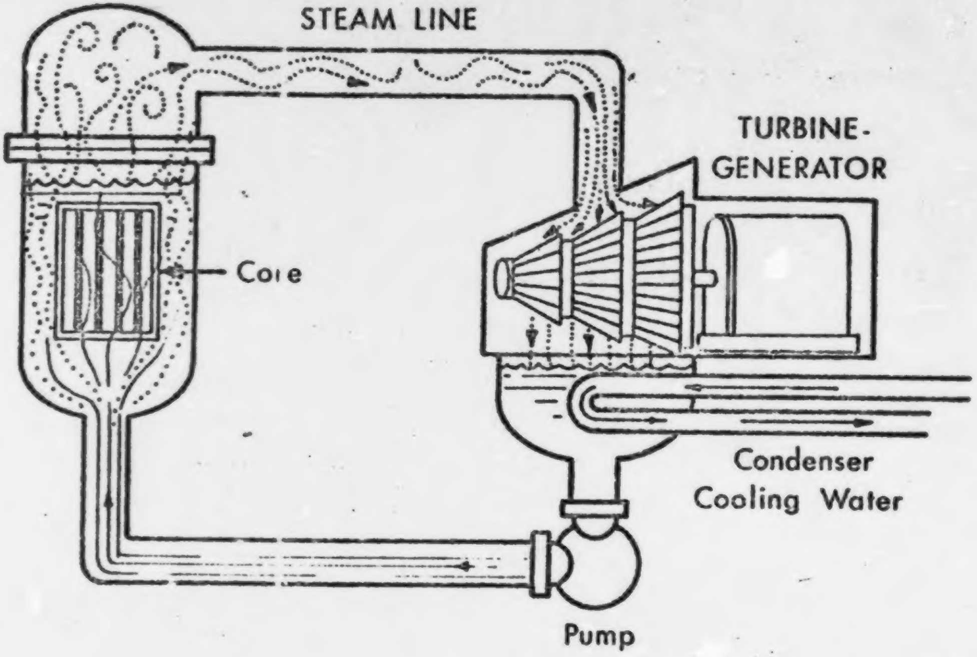
4. Gas - gases or air serve as the heat removal material.

THE NEUTRON CYCLE
(Thermal Reactor Fueled with ^{235}U and ^{238}U)

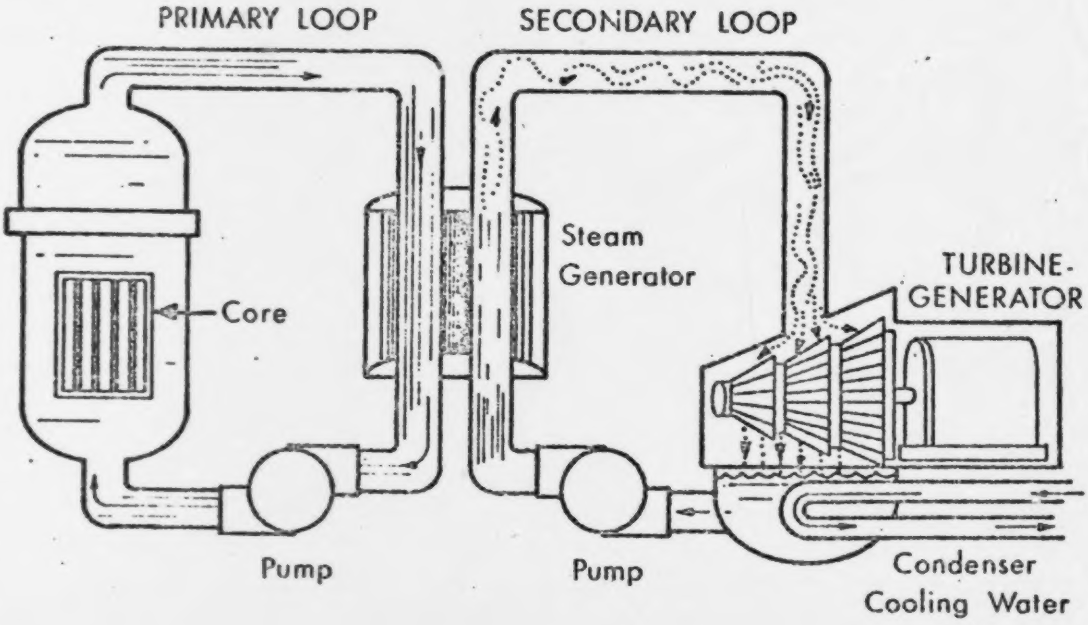

FISSION FRAGMENT
235U
FISSION FRAGMENT
238U
FISSION (FAST) NEUTRONS
FAST LEAKAGE
RESONANCE ABSORPTION IN 238U TO YIELD 239PU
MODERATOR
SLOW LEAKAGE
THERMAL ABSORPTION IN 238U TO YIELD 239PU
THERMAL (SLOW) NEUTRONS
ABSORPTION IN STRUCTURAL MATERIAL, MODERATOR, COOLANT, FISSION PRODUCTS, ETC.
235U

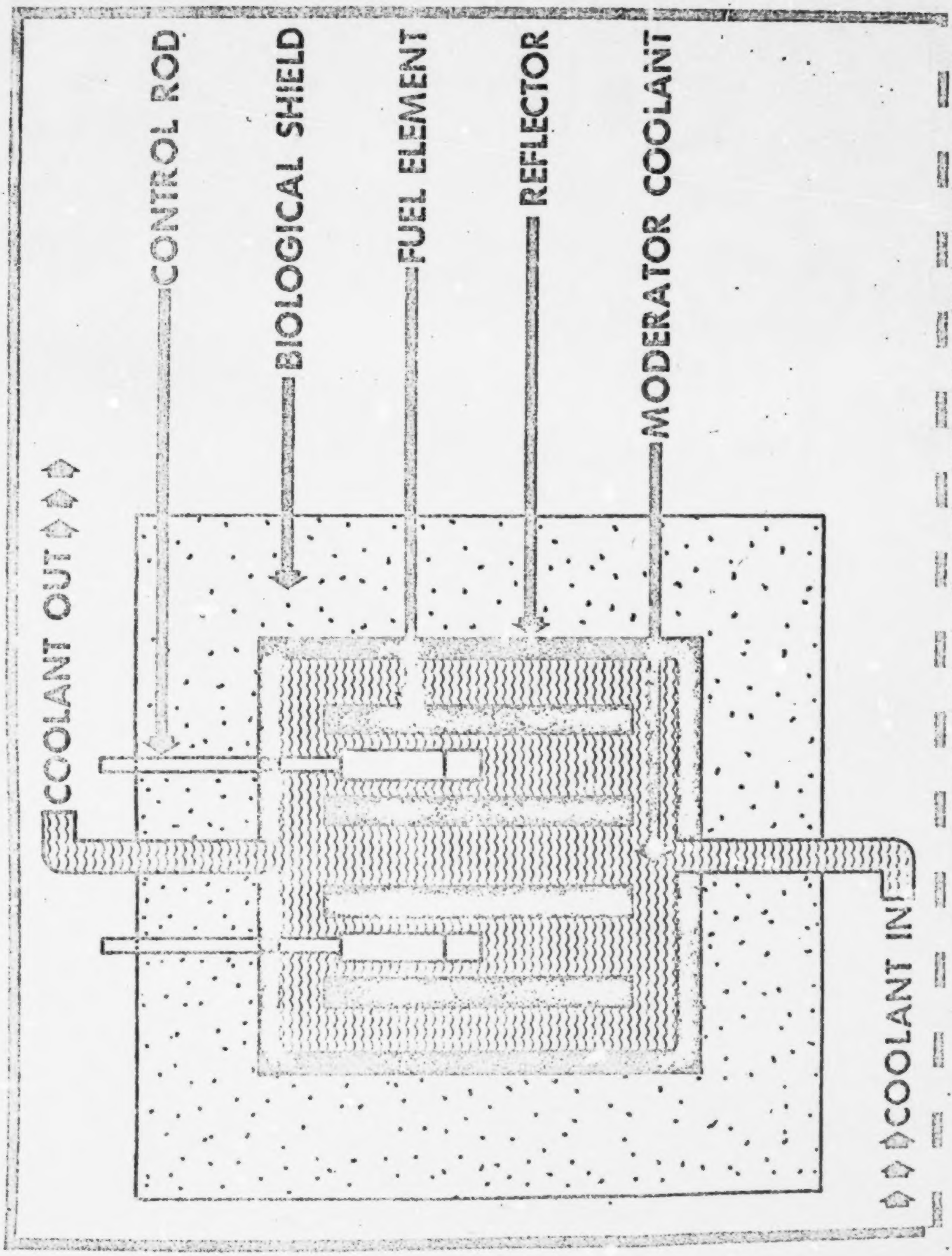
After Kaplan, I., "Nuclear Physics," Addison-Zesley Publishing Company, Inc., Cambridge, Massachusetts (1955).

BOILING WATER REACTORS


STEAM LINE
TURBINE-GENERATOR
Core
Condenser Cooling Water
Pump

PRESSURIZED WATER REACTORS


PRIMARY LOOP
SECONDARY LOOP
Steam Generator
TURBINE-GENERATOR
Core
Pump
Pump
Condenser Cooling Water


CONTROL ROD
BIOLOGICAL SHIELD
FUEL ELEMENT
REFLECTOR
MODERATOR COOLANT
COOLANT OUT
COOLANT IN

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Nuclear Detonations and Fallout

I. INTRODUCTION

Whether detonated in the air, on the earth's surface, under water, or underground (if venting occurs), testing of various nuclear and thermonuclear devices results in the release of materials to the troposphere and occasionally to the stratosphere. (The latter occurs principally as a result of larger explosions.) These radioactive materials can be gaseous or particulate in form and consist of fission products, unfused or unfissioned nuclear materials, and isotopes formed by neutron activation of earth and of debris from structures near the test.

Depending upon the altitude and physical-chemical nature of these particles, they fall back to earth under the influence of gravity and meteorological conditions during a span of seconds to years. When they make contact with the terrestrial and aquatic environment, these materials are more properly called fallout. The terms rainout and snowout may also be used as sub-categories of fallout. This return of radioactive materials to the biosphere via fallout is of health concern because the ultimate deposition of fallout radionuclides in various human "critical organs" may produce long-term biological damage.

II. NUCLEAR AND THERMONUCLEAR DEVICES WHICH CAN CAUSE FALLOUT

Three basic types of devices have been tested for warfare applications: bombs, rocket warheads, and artillery shells. Nuclear explosives used for Plowshare activities are special designs that are being developed for excavation, underground engineering, and other applications.

A. Fission Device (Also called Atomic or Nuclear Weapon)

This device utilizes only fissionable material such as uranium-235 or plutonium-239. The first nuclear device was detonated on a tower at Trinity Site, New Mexico, on July 6, 1945. A blast equivalence of about 20 kilotons of trinitrotoluene (TNT) is common for such a weapon. Both gun-barrel and spherical assemblies have proven successful. The devices may be made small enough to fit into an artillery or bazooka shell.

B. Fission-Fusion Device (Also called Hydrogen or Thermonuclear Weapon)

This device is a combination of a fission device and fusionable material such as deuterium and tritium. The fission releases tremendous quantities of heat which initiate fusion reactions. Fusion events, in turn, release enormous quantities of energy and very high-speed neutrons. The first experimental thermonuclear device was detonated by the United States in the autumn of 1952 at Eniwetok in the Pacific.

III. RADIOACTIVITY PRODUCED AND DISPERSED BY NUCLEAR DETONATIONS

Three types of radioactive material are produced and dispersed by nuclear detonations. These are: unfissioned weapon materials, mixed fission products, and materials with induced activity.

A. Unfissioned Materials

In the earliest designs, detonation efficiencies were low. This means that quantities of unfissioned uranium and plutonium remain after the detonation and can be detected near the site. The extremely toxic radioactive and chemical properties of these materials indicates that their ingestion and inhalation must be avoided. In general, however, unfissioned materials will not appear in significant amounts beyond the distance at which blast and radiation effects are severe.

B. Mixed Fission Products

The activity of the fission products produced in a nuclear explosion represents millions of curies. One minute after the detonation, the gamma activity of the fission products for each kiloton is equivalent to that of 30,000 tons of radium in equilibrium with its daughter products.

Since many of the primary fission products are very short-lived, the radioactivity will decrease rapidly at first. Then the apparent half-life of the mixed fission products will increase with age.

Thus, the dose from this mixture of radionuclides dies away according to the data in Table 1.(1)

Table 1.--Relative Dose Rate from Fission Products*

Time After Detonation	Relative Dose Rate
1 minute	137,000
1 hour	1,000
1 day	20
1 week	2
1 month	.31
1 year	.008
10 years	.00004

*This may be expressed in any unit (i.e., R/hr.) since these are relative values.

Three fission products of biological importance are strontium-90, cesium-137, and iodine-131. It has been estimated that all detonations by the United States, the United Kingdom, France, and U.S.S.R. through 1962 produced approximately 19.3 megacuries of ^{90}Sr, 30 megacuries of ^{137}Cs, and 15 megacuries of ^{131}I.(2)

C. Induced Radioactivity

The species and quantities of radionuclides formed by neutron bombardment depend largely upon the environment of the detonation site. Both short- and long-lived materials are formed, primarily by (n,γ) and (n, p) reactions, and their decay pattern is similar to that for fission products. Typical radionuclides formed in this manner during nuclear detonations are carbon-14, sodium-24, silicon-31, aluminum-28, chlorine-38, cobalt-60, zinc-65, manganese-54, and scandium-46.

It has been estimated that for air bursts 20,000 curies of carbon-14 are produced per megaton of weapon yield. Surface detonations give only about one-half this amount of carbon-14 since not as much atmospheric nitrogen is available for the reaction. The production reaction(3) is as follows:

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

Up until 1963, nuclear weapons tests were responsible for nearly 10 megacuries of atmospheric carbon-14. The amount of natural ^{14}C in the air is estimated as having been four megacuries before the tests, but this does not include the nearly 166 megacuries of natural ^{14}C found on the earth's surface.(4)

During the 1958 U.S. Pacific bomb tests, tungsten was intentionally incorporated into detonation devices so that radioactive tungsten-185 would be produced by a (n,γ) reaction. This radionuclide has provided valuable information on the rate of fallout and has been a tool for studying weather phenomena.(5)

IV. DETONATION FIREBALL AND THE PHYSICAL NATURE OF FALLOUT

After a delay of a few millionths of a second from the time of initial weapon detonation, a luminous gaseous sphere, called a fireball, is formed in the extremely hot atmosphere. The size of the fireball increases with the energy yield of the explosion. The maximum diameter may vary from 900 feet to over 3 miles. Luminosity of the fireball usually does not vary greatly with the energy equivalence of the bomb.

Vaporized bomb materials, water droplets, and debris condense to form the "atomic cloud" as the fireball increases in size and cools. This cloud is red or reddish brown when first formed because of the heat-catalyzed production of nitrogen dioxide, nitrous acid, and other nitrogen compounds from atmospheric gases and water vapor. Eventually the cloud changes to white, due to the water droplets present in it. On or near the surface, a strong updraft called "afterwinds" sucks dirt and debris up from the ground into the radioactive cloud. As the upward thrust of debris slowly subsides, gravity begins to retrieve particulates to the earth's surface. This causes a lengthening and widening of the columnar cloud; eventually, the debris disperses widely due to the jet stream, meteorological conditions, and the continued influence of gravity.

A. Types of Fallout Particles

Fallout particles may be grouped in three categories.

1. Plated-Type Fallout

Vaporized bomb products and induced activities which condense out as a thin shell coating on elevated particles of earth and debris form this type of fallout. Much fallout is of this nature, especially if the detonation takes place at a site relatively devoid of silicate sand.

2. Fused-Type Fallout

Bomb materials may undergo a thermal fusion with silicate to form minute, melted, glassy "beads" which contain air bubbles and mineral grains. These may be transparent to opaque in transmission of light and pale green or yellow to brown or black in color. Radioactivity is distributed irregularly throughout these spherical or irregular forms.

3. Droplet-Type Fallout

If a device is detonated near a body of water, large quantities of water may be vaporized in the fireball. As the vapor condenses out of the cooling atomic cloud, fission products and earth debris may be suspended in water droplets and then fall back to earth as precipitation.

B. Categories of Fallout

Fallout from near-surface bursts may be categorized according to the elapsed time between the time of detonation and complete descent to the earth.

1. First Fallout (also called Local Fallout)

About 80 percent of the radioactive particulates produced by a surface detonation is deposited within a few hours at a distance no further than a few hundred miles from the burst point. Particles which have a diameter of 400 microns, 250 microns, and 150 microns may fall from 80,000 feet in about 1½, 2½, and 5 hours, respectively.(1) It is this first fallout which constitutes the acute radiological hazard. Detonation of a single superweapon may contaminate an area of 5,000 square miles or greater with lethal levels of beta and gamma radiation.

2. Second Fallout (also called Tropospheric Fallout)

Fallout particles of smaller sizes and masses are deposited in the lower atmospheric layers (below 35,000 feet) and are gradually brought down in a matter of one to two months by ordinary weather phenomena. These tropospheric particulates may travel completely around the world in a shell-like fashion, but they usually stay in a rather narrow radioactive band which has the general latitude of the detonation site.

3. Delayed Fallout (also called Stratospheric Fallout)

This type of fallout is created by detonations of weapons of megaton size or greater which propel radioactive particulates of submicron diameters to heights of 16 miles or more. The estimated half-residence time of stratospheric fallout varies from 5 to 60 months. The longer half-residence times result from tropical injections at high altitudes (up to 250,000 feet).

V. DISTRIBUTION OF STRATOSPHERIC FALLOUT

The winds in the stratosphere are predominately easterly or westerly, depending on the time and place. Thus the radioactive cloud which reaches the stratosphere becomes drawn out in a windward direction to form a streak around the globe. The cloud gradually widens in the north-south direction, but changes in altitude are very slow.

Almost the only way for return of this radioactivity from the stratosphere is for the cloud to move into the troposphere where the particles can be brought down by precipitation.

This can happen in the arctic winter by downward movement of the debris through the tropopause, in the arctic spring because of an upward movement through the tropopause, or by turbulent circulation near gaps in the tropopause in each of the temperate zone.

A. Equatorial Testing

Equatorial zone bomb testing (11°N) apparently results in twice as much stratosphere fallout going to the Northern Hemisphere as to the Southern Hemisphere.

B. Large Detonations

In the higher latitudes of the Northern Hemisphere, large detonations apparently will deposit almost all resultant stratospheric fallout in that hemisphere with a mean stratospheric residence time of 1 year or less.

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Radium Accidents

I. INTRODUCTION

Radium has been used for over half a century and much of the experience with radioactive materials in medicine has been gained with this radionuclide.

Because it must be applied to or inserted into the patient and later recovered (and because in the intervening time, loss may occur) radium is perhaps more "accident prone" than other radionuclides used in medicine. Furthermore, radium sources when lost or damaged create greater potential hazards than other radionuclides in common medical use.

Although this discussion is concerned primarily with radium, the principles apply to some extent to all radionuclides.

II. RADIUM SOURCES

A. Construction of Sources

1. Radium tubes are intended for intracavitary therapy. They are usually made of platinum or platinum-iridium alloy, cylindrical in shape, with rounded ends and eyelet at one end. They are about 3 mm external diameter and 15-40 mm in length. They may contain from 1 to 50 mg of radium, and may be direct-filled or cell-filled, that is, the radium salt may be placed directly in the tube, or may be placed in a thin tube called a cell, which is inserted in the tube. One end of the tube consists of a plug which may be screwed in, force-fitted, or silver soldered.

2. Radium needles are intended for interstitial therapy. They are similar to radium tubes, but are thinner and have one end pointed. The radium content of a needle is usually 10 mg or less.

3. Radium plaques are intended for treatment of superficial skin lesions. They are flat applicators, circular, square, or rectangular in shape, 1 to 4 cm^2 in area, containing up to 20 mg Ra deposited on the inner surface of a thin model face.

B. Potential Hazards

1. Radium for filling tubes and needles is in the form of a finely divided salt (usually sulfate, but may also be chloride or bromide). Thus it is easily dispersible.

2. The decay product of radium is radon, gas which is also radioactive. Being a gas, it can be spread by diffusion, even from a fixed source.

3. As a contaminant of material, radium is essentially permanent because of its long (1620 year) half-life. In other words, we cannot depend upon decay to remove the contamination. (cf P^{32}, I^{131})

4. As a source of internal exposure, radium is extremely toxic. It is an alpha emitter, it deposits in the bone, and has a low excretion rate.

III. ACCIDENTS

A. Lost Sources

Radium may be discarded with contaminated dressings and be carried to the hospital incinerator or city dump. It may become dislodged from the body cavity under treatment and dropped into a bed pan or toilet and thence carried into the sewage system. The small size of radium sources, and the fact that many hospital attendants would not recognize a source when they see one, renders early detection unlikely.

The matter of greatest concern is not the financial loss, as this is covered by insurance, but the hazard potential. The source may fall into the hands of a person who does not recognize it but who may keep it as a trinket or curiosity and thereby receive excessive external exposure. Or the source may be damaged, resulting in widespread contamination and potential internal exposure.

B. Damaged Sources

Sealed radium sources for medical use are usually considered and handled as though they are homogeneous solid objects not subject to damage or change. We are rudely reminded that this is not the case in those instances, fortunately rare, when a radium tube or needle is damaged or undergoes deterioration and the radium salt is no longer fully contained but spills out or slowly leaks out and causes contamination of material and possible injury to personnel.

1. CAUSES OF DAMAGE

a. Excessive pressure in the source container can result from accumulation of helium, radiolytic decomposition of water in incompletely dried radium salt, and heat from sterilization or fire.

b. Breakage due to inherent defect in metal.

c. Loosening of plug in end of tube or needle.

d. Mechanical damage, such as crushing underfoot.

2. POSSIBLE CONSEQUENCES OF RUPTURED SOURCE

a. Leakage of Ra during interstitial or intracavitary use, resulting in uncontrolled internal exposure to patient.

b. Inhalation or ingestion of radium salt by person working in close proximity to source.

c. Transport of radium salt to other areas on the shoes or clothing.

d. Transport of airborne radium salt via heating and air conditioning ducts, or in the air stream of electric fans, resulting in inhalation of radium salt by persons in remote areas.

IV. ACTIONS TO BE TAKEN IN CASE OF A SPILL

A. Proper management of a spill as soon as it is recognized may prevent exposure of persons and will minimize financial loss due to contamination. This applies to all radionuclides.

B. Instructions for handling cases of spillage with sealed sources are given in NBS Handbook 54, Part 9, page 31-32. Portions of pertinent sections, 9.21 and 9.22, are quoted below:

"If there is reason to suspect that a disruption of a sealed source containing an isotope has occurred, the following emergency measures shall be taken at once:

(a) No immediate attempt shall be made to clean up the spill.

(b) All windows shall be closed, fans and air-conditioners shall be shut off, and everyone shall leave the room.

(c) All doors shall be closed and locked.

(d) If powdered or gaseous sources are involved, the door and all other openings leading into the room shall be sealed with wide masking tape or adhesive tape and heavy wrapping paper.

(e) Every person who might have been contaminated shall be tested for radioactivity, and, if contaminated, shall remove his clothes and be decontaminated. If no means are available for testing, it shall be assumed that the person is contaminated.

(f) Entrance to the contaminated area shall be prohibited.

(g) A consultant experienced in radiation hazards should be called in and his advice followed.

(h) In radium accidents, portable alpha meters shall be obtained so that adequate decontamination can be carried out.

Under no circumstances shall any untrained person attempt to examine or clean up any spilled radioactive material. (The cleanup technique should be planned with the same care as is used in quantitative chemical analysis or in bacteriological handling of extremely virulent organisms.) Fans or ventilating apparatus should not be turned on in an attempt to blow away the isotope or its decay products. Such a maneuver will only disseminate the radioactive material throughout the area. If the isotope is blown out of a building, air currents may carry the finely divided material into nearby windows or air-intake ducts. Proper precautions taken immediately will protect human life and and minimize financial losses."

NBS Handbook 48 contains instructions for dealing with the special problems associated with the spillage of liquid sources.

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Radioactive Contamination Monitoring

I. INTRODUCTION

Radioactive contamination may exist in a wide variety of forms in laboratory or industrial installations. It may be in the form of dusts, liquids, mists, gases, or fumes with each category requiring specific monitoring techniques. Other factors of equal importance are: the types and energies of radiations emanating from the contaminant, amounts of contaminant deposited on surfaces, its physical and chemical composition, and any external forces which act upon the contaminant. A monitoring program adequate to cope with all of these factors must have considerable versatility.

II. SUSCEPTIBILITY

A. Contamination may appear in or on all of the following places and objects:

1. Floors, corridors, loading docks, elevators, and other frequently traveled areas.

2. Horizontal surfaces such as bench tops, filing cabinets, window sills, exposed light fixtures, and ledges.

3. Objects frequently handled by laboratory workers such as telephones, books, chairs, and door knobs.

4. Cleaning equipment such as mops, mop buckets, brooms and buffing machines.

5. Sinks, wash basins, plumbing fixtures, sink traps, and drain lines.

6. Tools used in repair of sinks, sink traps, and drain lines.

7. Areas through which air currents pass, such as ventilating ducts, filters, screens, door louvers, and door key holes.

III. MONITORING TECHNIQUES

No single monitoring technique can be applied in all types of contamination problems. Usually more than one technique is necessary and may require smears, portable survey instruments, and air samplers.

A. The smear technique can be used to detect transferable surface contamination.

1. This involves:

a. Rubbing a piece of filter paper (usually Whatman No. 50, 4.25 cm diameter) over a surface area of 100 sq. cm.

b. Counting the smear in an appropriate counter for alpha, beta, and gamma activity.

2. The smear technique can be used most effectively as a check on contamination control measures and as a method for determining the thoroughness of decontamination efforts.

3. Smearing is a qualitative method although considerable emphasis is placed on quantitative results.

B. To determine the magnitude of fixed surface contamination, some type of portable survey meter is usually used in conjunction with the smear survey. Examples are:

1. Alpha survey meters

a. Specific types include the proportional alpha counter (PAC-3G), Sampson, Juno and alpha scintillation counters

b. The PAC-3G and most scintillation instruments can be biased and made insensitive to beta-gamma radiations.

c. Alpha monitoring, regardless of instrument sensitivity, is a tedious and time consuming process.

2. Beta and Beta-Gamma Survey Meters

a. The Cutie Pie, Junio, GM Survey Meter, and special scintillation survey meters are used to detect and measure beta and beta-gamma activity.

b. The GM Survey Meter is the best detection device for beta-gamma activity. It is widely used as a beta detector since it has a rather high (~90%) efficiency for beta particles. It should not be used as a dose determining device due to its low efficiency for gammas and its inherent "ability" to jam in high radiation fields.

c. The Juno and certain scintillation survey meters may also be used as beta and beta-gamma detectors, however, it is usually difficult to detect low levels of surface contamination with the Juno type.

d. The Cutie Pie is one of the best "dose rate" instruments available for measuring gamma activity.

e. When provided, head phones should always be used with survey meters since the audible signal is more representative than the meter fluctuation.

C. Air sampling techniques are also important in monitoring for contamination.

1. Portable pump samplers

a. Such samplers utilize a filter through which is pumped a constant flow of air.

b. The filter can be removed after a predetermined sampling period and counted in conventional counters.

c. The contribution due to thoron and radon daughter products must be considered in the counting analysis.

d. One may use low volume (1-2 cu. ft. per min.) or high volume (50-150 cu. ft. per min.) portable samplers to obtain a representative sample.

e. Air samples should be taken at a height representative of the occupants breathing zone.

2. Continuous air samplers (beta-gamma)

a. The fixed filter GM tube type continuously samples and records the beta-gamma activity in a given zone.

b. The tube must be shielded to provide a low background.

c. It affords an excellent but rather expensive method of constant atmospheric surveillance.

3. Continuous air samplers (alpha)

a. These may consist of a ZnS (Ag) photomultiplier, and an end window GM tube balanced so that the contribution made by radon and thoron daughter products collected on a moving tape filter is zero. Any deviation from this set pattern can be attributed to long-lived radionuclides present in the sample.

4. Detection of extremely low levels of alpha emitters such as Pu^{239} (Radioactivity Concentration Guide of 13 d/m per cubic meter of air) is difficult by any method.

IV. SPECIAL MONITORING TECHNIQUES

A. Certain contamination problems may necessitate the use of:

1. Hand and foot counters which are AC powered multiple GM tube type instruments specifically designed for checking the hands and feet for beta-gamma contamination.

a. Openings are provided for insertion of the hands and equipped with a platform on which to place the feet.

b. An automatic scaler-timer controls the counting sequence for each of 5 channels.

(Back and palm of each hand and soles of shoes)

c. Some models are equipped with a GM tube probe to permit clothing checks.

d. Such instruments will not detect alpha activity and are limited in low energy beta detection.

2. Portal monitors or "Friskers" may be installed around door openings to check on clothing contamination of individuals passing through. These:

a. consist of 5 unshielded GM tubes located around the door frame and a 5 channel AC powered scaler.

b. require a low background since GM tubes are unshielded.

c. will detect contamination levels on a person's clothing in the region of 1 mrad/hr and will alarm if set point is exceeded.

3. GM tube laundry monitors are used to check clothing contamination both before and after laundering.

V. SPECIAL TESTS

A. Sealed source leak tests are necessary to minimize the possibility of contaminating the source holder and surrounding areas.

1. Sealed sources may develop leaks by:

a. increased internal helium pressure from alpha decay; a particular factor in radium, plutonium, and polonium sources.

b. presence of water vapor within the source capsule. Gas pressure buildup in this case is even faster than that of helium buildup.

c. attack by chemicals and corrosive fumes.

d. physical damage from vibration, shock, or undue mechanical stress.

e. deterioration of the capsule materials (e.g., loss of solvents from plastics, etc.).

2. Sources should be tested regularly (monthly is recommended) by one or more of the following methods.

a. Smear source capsule and count smear for surface contamination.

b. If source contains radium, place it in a plastic test tube, tamp with cotton and stopper. Should radon be escaping, the cotton will tend to trap daughter products. Survey cotton with GM survey meter.

c. After cleaning capsule, place in a water bath for several days. Run a radiochemical analysis on water bath for presence of source constitutes or decay products.

3. There are numerous methods for testing sealed source integrity. Regularity with any given method is probably most important.

VI. CONTAMINATION LIMITS

A. To provide some criteria for contamination control, it is essential to adopt realistic maximum levels of contamination.

1. NBS Handbook No. 69 lists current maximum levels of radionuclides in air and water for occupational application.

2. The following tables are examples of contamination limits used at some AEC facilities.

Criteria for Contamination Zones

Type of Radiation	Airborne Contamination (μc/cc air)	Direct Reading Surface Contamination	Transferable Surface Contamination (dpm/100 sq. cm)
Alpha	5×10^{-11}	300 dpm/100 sq. cm	30
Beta-Gamma	1×10^{-8}	0.25 mrad/hr	1000

Maximum Contamination Limits for Skin Surfaces

Surface	Direct Survey		Transferable (Smear)	
	Alpha	Beta-Gamma	Alpha	Beta-Gamma
	(dpm/100 sq. cm)	(mrad/hr)	(dpm/100 sq. cm)	
General Body	150	0.06	Nothing Detectable	
Hands	150	0.3	Nothing Detectable	

Maximum Contamination Limits for Clothing

Item	Direct Survey		Transferable (Smear)	
	Alpha	Beta-Gamma	Alpha	Beta-Gamma
	(dpm/100 sq. cm)	(mrad/hr)	(dpm/100 sq. cm)	
Shoes, Contamination Zone				
Inside	300	1.0	30	1000
Outside	300	2.5	30	1000
Shoes, Personal				
Inside	300	0.3	30	200
Outside	300	0.6	30	200
Clothing, Contamination Zone	150	0.6[a]		
Clothing, Personal	150	0.25		

[a] The average reading shall not exceed 0.6 mrad/hr. in any 644 sq. cm (100 sq. in.) area.

Criteria for Contamination Clearance[b]

Direct Survey		Transferable (Smear)	
Alpha	Beta-Gamma	Alpha	Beta-Gamma
(dpm/100 sq. cm)	(mrad/hr)	(dpm/100 sq. cm)	
300	0.05	30	200

[b] "Clearance" as used here applies to transfer of items to clean shops, storerooms, offices, etc., within the plant area, transfer of such items within the controlled vicinity or to items being released to the general public.

Applying the above levels to smears, an IPC counting rate of 15 c/m/100 cm^2 smear of alpha and 100 c/m/100 cm^2 smear of beta or a G-M counting rate of 20 c/m/100 cm^2 smear of beta would be the MPL. It has been found that it is possible and practical to maintain levels 10 times less than this.

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GPO 921-907

Emergency Monitoring Techniques for Food and Water

I. INTRODUCTION

This lecture will be devoted to a discussion of emergency monitoring techniques for food and water following the release of fission products from a reactor excursion or detonation of a nuclear device.

II. APPROACH TO HAZARD EVALUATION

A. Upon release of radioactive materials to the environment, three possible types of hazards require immediate evaluation: (1)

1. The external radiation hazard;
2. The inhalation of activity; and
3. The ingestion of activity from contaminated food and water.

B. It is the function of personnel in charge of the environmental survey to assess these three factors and to provide quickly the basic information upon which action should be initiated. Such an environmental survey can be broadly divided into two parts:

1. Physical survey involving direct radiation measurements and air sampling.
2. Biological monitoring involving the sampling and analysis of biological materials.

Experiences such as at Windscale (1) and evaluations of fallout at distances far from the site of nuclear weapon detonations indicate that internal exposures resulting from ingestion and inhalation of radioactive materials are more important than external exposures. Hence emergency monitoring techniques for food and water are very important in the assessment of the hazard due to nuclear accidents.

C. The nature of the radionuclides making up the contamination is very important in assessing the hazard. The relative activity of the more significant radionuclides at specified times following detonation of a fission type weapon is presented in Table I.

Table I

Relative Activity of Significant Nuclides (3)

Nuclide	Time After Bomb Burst			
	12 hrs	1 day	2 days	10 days
Sr^{89}	1	1	1	1
Sr^{90}	0.006	0.006	0.006	0.007
Sr^{91}	68	28	5	0
Ba^{140}	5.4	5.3	5.0	3.6
La^{140}	1.1	2.2	4.5	3.7
All Fission Products	1000	420	170	36

In special circumstances, such as at Windscale, other radionuclides may assume importance (i.e., Iodine-131 and Cesium-137). Consideration of the circumstances of the release or initial monitoring, however, should soon establish the presence of these materials.

III. MONITORING PROCEDURES

Monitoring of a nuclear emergency will generally consist of two distinct operations--field surveys followed by laboratory measurements. Although each type has certain advantages, both must be used to provide complete surveillance.

A. Field Surveys

Generally, when radioactive materials are released to the environment, food contamination will first appear in the rapidly produced items such as milk, eggs, and fresh garden vegetables. Foods such as meat, fish, nuts, and fruits will tend to have a latent period before contamination levels reach their peak. Thus earlier sampling operations should be directed principally toward the former group of foods.

Suggested emergency levels (2) are high enough to be measured with portable survey meters. For example, Tait and Merritt (3) have calculated gamma fields using the United Kingdom emergency permissible intake of 30 μc Sr^{89} plus 150 μc Ba^{140} ingested over a 10-day period. (Allowances are also made for Sr^{91} (plus Y^{91}), and La^{140}). These data are presented in Table II. Ingestion at these levels is expected to lead to a dose of 5 r to the sensitive volume of the bones.

Although the levels listed in Table II are for radioactive materials in water, they are readily adaptable to the monitoring of food samples. With longer periods of consumption, the initial concentration need not be reduced proportionately since much of the Ba^{140} activity will have decayed prior to ingestion. For example, the gamma fields corresponding to the permissible concentration for 30-day ingestion are found to be one-half those given above for 10-day ingestion.

Table II

Gamma Radiation Fields* From Permissible Levels of Fresh Fission Products in Drinking Water (3)

(Dose Rates are Expressed in Milliroentgens Per Hour)

Object Monitored	Time After Bomb Burst			
	12 hrs	1 day	2 days	10 days
Large body of water	104	49	23	13
Tank truck (1000 gal.)	68	32	15	8.5
4 Gal. Jerry can	28	13	6	3.5
2 Gal. oil can	25	12	5.5	3.0
Water bottle (1 liter)	13	6	3	1.5

*Fields are to be measured at the center of one surface and correspond to the ingestion of 30 μc Sr^{89} plus 150 μc Ba^{140} over a 10-day period.

The Office of Civil and Defense Mobilization has distributed calibrated standards for determination of acceptable emergency levels in water. Each standard consists of a known quantity of radioactive material deposited in a shallow dish and designed to yield the same reading as a similar container full of water contaminated to the acceptable emergency concentration for 10-day consumption.

Although for 10-day old activity and small samples it may be necessary to resort to more sensitive laboratory instruments, in general the levels in Table II lie within the range of the G-M type survey meter and the gamma scintillation meter. Thus it is apparent that the first line of monitoring will be done with portable survey meters. It is of utmost importance to have a system of calibration, maximum permissible acceptable emergency levels, technical equipment and assistance set up before the emergency. Once the need arises, a system of where and what to monitor must be efficiently administrated. Use should be made of meteorological data, external gamma levels, air activity and source strength to predetermine the extent of contamination.

B. Laboratory Monitoring

Where greater sensitivity or isotopic analysis is desired, laboratory techniques should be employed, for monitoring. If changes in the radionuclide composition of the contamination are suspected (due, for example, to increasing age of the material or selective absorption by the environment), a radionuclide analysis should be performed.

In any expected excursion several thousand samples will probably be taken. The only laboratory method for processing large numbers of samples, without excessive manpower, is gamma spectral analysis. To further increase the sample capacity, a scintillation detector can be connected to a scaler and gross gamma counts taken routinely with supplementary spectral analyses on a spot-check basis. The internal proportional counters and geiger counters can also be used but sample preparation and interpretation of the data poses problems.

Once the radionuclide composition of the contaminant has been determined, the hazard can be evaluated in terms of ICRP and NCRP recommended values. (4) It is suggested that some appropriate multiplying factor can be applied to the occupational values for the emergency exposure.

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Introduction To Reactor Incidents

I. LAND BASED UNITS

A. Acute Hazards

The probability of a reactor accident is quite small, being estimated at one chance in 10^5 to one chance in 10^9 per reactor per year, but the hazards associated with such an event are considerable and constitute a severe threat to the health, safety, and welfare of both the plant personnel and general public.

It is possible to conceive of accidents which would release the accumulated fission products from a large reactor in a finely divided state so that a significant portion of them would become airborne and subject to atmospheric dispersal over wide areas. Injury or death could result to people from exposure to the direct radiation from these materials, or from ingestion of a fraction of them into the body. Settling out of these materials could cause both further hazard to health and costly contamination damage to property. Death at distances of many miles and injury and property damage for hundreds of miles could conceivably result.

1. TYPES OF ACCIDENTS

Only a few types of reactor accidents could plausibly lead to a release of fission products to the atmosphere. These are:

a. Nuclear runaway

A nuclear runaway would result if the reactor were made supercritical and all safety instrumentation failed to function. The possibility of a serious runaway cannot be completely ruled out, but its occurrence can be made extremely unlikely by:

1) careful operating procedure
2) adequate design
3) a multiplicity of control devices

b. Loss of coolant

This type accident could result from a break in the primary coolant circulating system or from a rupture of the reactor vessel itself. Loss of coolant would permit the radioactive decay heat to melt the uncooled fuel, even though the nuclear reaction had stopped, and thereby permit release of volatile fission products. Control of such an accident is largely dependent upon:

1) adequate design
2) care in construction
3) provision for emergency cooling of the core

2. FACTORS DETERMINING A MAJOR ACCIDENT

To estimate the safety of a given reactor is difficult. Factors influencing such an estimation include both those of a positive as well as those of a negative nature.

a. On the positive or preventive side are factors such as:

1) In no reactor, so far as is known, will a single equipment failure or single operating error lead to a fission product releasing accident.

2) Most reactors, because of negative temperature or power coefficients, are inherently stable.

3) Metallic cladding of fuel in heterogeneous reactors restricts the escape of fission products except upon meltdown or violent damage.

4) In homogeneous reactors, continuous removal of fission products affords a means of keeping releasable inventories to a minimum.

5) The possibility of total release of fission products is remote.

a) Seventy-five to 80% of the fission product elements are solids at ordinary temperatures.

b) Those products most likely to be released include those which decay most rapidly.

6) A primary containment vessel enclosing the reactor provides a major safeguard against fission product release; a vapor shell enclosing the whole installation is designed to contain all fission products that might be released in any credible accident.

7) The probability of the right combination of meteorological conditions which would give rise to the most unfavorable effects (should a release occur) is extremely low.

8) The major threat to the safety of people remote from the site of release would not be instantaneous. Periods up to hours and even days after release should be available within which to avoid the full effects of the radiation.

b. On the negative side, contributing to a major accident, are such factors as:

1) Many power reactors operate under high pressures. Such systems are subject to failure.

2) The cumulative effect of radiation on physical and chemical properties of materials (after long periods of time) is largely unknown.

3) After initial operation, many components of the reactor system become inaccessible for inspection.

4) Various metals used in reactors may react explosively with water.

5) Much remains to be learned about the characteristics and behavior of nuclear systems.

6) At the present stage of development, the operation of a reactor requires human control and consequently such operation is subject to some degree of human error.

3. ENVIRONMENTAL CONSEQUENCES

Evaluation of the hazardous consequences to the environment (and public) of a reactor accident depends upon a number of factors. Those considered most important include:

a. Size and location of the reactor

The fuel loading and fission product inventory in a power reactor will depend upon its power level, length of operation, and the frequency of refueling. Since large volumes of water are required for condenser cooling, most power reactors will be located near sizeable streams. Also, they will be located near areas having large energy requirements (i.e., large cities). The location of the reactor will also influence other conditions having an effect on the environmental consequences of a release of fission products. These include:

1) Meteorological conditions

The distribution of released products is greatly influenced by such factors as wind speed and direction, temperature, turbulence, etc.

2) Topography of the area

This determines the distribution of deposited rain and fallout on land and water surfaces.

b. Personal injury (immediate)

Personal injury may result from exposure to the radioactive cloud and fission products deposited on the ground, as well as their inhalation. The extent of exposures from the radioactive cloud appears to depend, as previously discussed, upon the nature and extent of the fission product released. In the case of fission products deposited on the ground, ample time may be available to permit evacuation of personnel from contaminated areas before serious injury. Evaluation of the hazard to individuals depends upon assumed criteria. A maximum dose of 25 rems is generally used in the literature. However, many health personnel believe a definite need exists for further evaluation of such criteria and the matter is currently under study.

c. Surface contamination

Factors influencing the evaluation of fission products reaching the general environment include:

1) land use

Land contamination could cause curtailment of its use for agricultural purposes (or as pasture).

2) water sources

Deposition of fission products on water reservoirs or major water sheds could lead to abandonment of selected water sources. Generally, well water supplies should be unaffected.

d. Emergency planning

Certain factors appear to assume importance in emergency planning:

1) alternate food and water sources

In most instances in peace time, it would be assumed that personnel would be evacuated from contaminated areas. However, in certain cases, external exposure levels may remain low enough to permit them to remain. Under these conditions, it would appear that alternate sources of food and water may be indicated or special decontamination procedures might be employed until such time as radioactive levels decrease to permissible levels. Here again, a definite need exists for official criteria for determining the degree of acute hazard. In particular, emergency Radioactivity Concentration Guides for food, milk, water, and air need to be indicated. The Federal Radiation Council has indicated it plans to take this matter into consideration within the very near future.

2) other factors

Other factors considered of importance in the overall evaluation of environmental problems arising from reactor accidents include:

a) evacuation procedures

Here, civil defense planning might be of assistance.

b) communications

Of extreme importance in directing evacuation.

c) emergency medical care

d) psychological effects

B. Chronic Hazards

1. NATURE AND EXTENT OF RADIOACTIVITY RELEASES

The potential wastes produced would vary with each reactor installation depending on the type of reactor and extent of supporting operations.

a. Fission products would be present in any fuel reprocessing wastes and to a lesser degree in coolants, laundry wastes, and other miscellaneous discharges.

b. Induced radionuclide wastes might also be a problem in wastes such as reactor coolants.

2. ENVIRONMENTAL SURVEILLANCE

The overall magnitude of the surveillance program would depend on the extent of the potential waste hazard in relation to the environment resources which might be deleteriously affected. As such, the specific program must be tailored to the needs of each individual reactor site.

a. Sampling may include air, water, soil, and plant and animal life. These are necessary to establish preoperational levels. Pertinent samples, which would reflect the maximum influence of wastes discharged, should be taken periodically following operation of the reactor. In addition to the legally required samples of water and air, these should include food-chain and other indicator materials.

b. Analyses would routinely include gross beta determinations. Specific radionuclide analyses should be made on "hot" samples or on a spot-check basis.

c. Criteria for the management of waste discharges vary. No set tabulation of concentration or daily output can be recommended for all sites. A basic approach, however, might be to limit discharge concentrations to some percentage of RCG values. The specific percentage chosen would depend on such factors as the importance of the environmental resources contaminated and the number of other reactor installations discharging into the same resources.

d. As to legal responsibility, industry should conduct or financially support the survey and open its records to the public. State and local health departments should conduct check surveys to ensure the validity of reported data.

II. THE IDEAL REACTOR HAZARDS REPORT

In summarizing the overall problem of nuclear reactor safety evaluation, there are certain necessary ingredients for an ideal hazards report. Such a report should consider all facets of the problem, and from the standpoint of the acute hazard, provide answers to the following questions:

A. What is the likelihood that fission products might be released?

B. What are the factors and conditions which would affect the distribution of released materials over public areas?

C. What are the levels of exposure or contamination which cause injury to people or damage to property?

D. If releases of fission products should occur, what deaths or injuries to people and costs in damaged property could ensue?

In connection with the last question, there should be some guidance afforded public health officials as to what they can do to minimize these effects. In particular, the hazards report should present in detail:

1. The routine monitoring system established for detection of a major reactor failure.

2. How long it will take to recognize such a condition.

3. The time lag before local health authorities will be alerted.

4. How soon local officials can be operative.

It is generally agreed that existing hazard reports leave much to be desired from the standpoint of public health officials. Such reports are not being written for this particular audience - yet such officials undoubtedly have need for reactor hazard information.

Most existing reports cover the acute hazard phase in some detail. If, however, the probability of a major reactor accident is as remote as these reports indicate, should not the chronic type of hazard be given equal consideration? Such an evaluation might be issued as a second volume supplementing existing hazards reports.

There is a need for wider dissemination of reactor hazard reports, specifically, to responsible officials in the state, county, and city, where the reactors are to be located. For each reactor being planned, constructed, or operated, it would be desirable to have designated a specific individual or office to which local health officials can turn for information and answers to specific questions.

BIBLIOGRAPHY:

"Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," Steering Committee, Dr. Clifford K. Beck, Chairman, U.S. Atomic Energy Commission Report WASH-740, March, 1957.

Causes, Effects, and Control of Reactor Incidents

I. INTRODUCTION

The growth in the use of reactors accentuates the need to analyze the potential environmental hazards associated with these operations. Although it is clear that widespread environmental problems could result from the uncontrolled release of radioactive materials from a reactor, the fact remains that the safety record of reactor operations has been outstanding.

A. To analyze the potential hazards and to reduce the consequences, it seems appropriate that we attempt to find answers to the following questions:

1. What type of and how much activity may be generated and released during a reactor incident?

2. How can we classify reactor operations and incidents to evaluate the hazards and to provide the means for protection?

3. What are the sources or causes of reactor incidents and how may they be counteracted?

4. What are the consequences of an incident?

5. What plans can be devised to reduce the probability and the consequences of an incident?

B. Consequently, we shall concern ourselves with a discussion of the generation of activity, the classification of reactor incidents and emergency plans. Each of these areas of concern will be discussed in the same order as presented above.

II. GENERATION OF ACTIVITY

Criticality incidents have in the past involved the generation of 10^6 to 10^8 curies of activity in short periods of time as indicated in Table 1. A 1 mw-sec incident may involve the fissioning of 3×10^{16} atoms of U or Pu and the generation of approximately 3×10^6 curies of beta activity measured at 1 second after the incident. This activity decays at a rate of $(t_2/t_1)^{-1.2}$. For example, if t_1 is 1 second after the incident and t_2 is 7 seconds after the incident, the activity at 7 seconds would be 1/10 of the activity at 1 second. The activity at 7 hours would also be 1/10 of the activity at 1 hour. A summary of the essential relationships of fissions, energy and activity is presented in Table 2. The operation of a reactor over an extended period of time will cause the build up of longer lived fission products. The total activity will then decay at the rate of

$$t_1 \left[\left[\frac{t_2}{t_1}\right]^{-0.2} - \left[\frac{t_o \quad t_2}{t_1}\right]^{-0.2} \right] \text{ or}$$

$$\left[(t_2)^{-0.2} - (t_o + t_2)^{-0.2} \right]$$ where t_1 is 1 second and t_2 and t_o are given in seconds. For long periods of operation the activity decays at the rate of $t_2^{-0.2}$ with respect to 1 second.

Table 1. Relationship of fissions to energy generated, activity and calories

Type of incident	No. of Fissions	Energy, in Mw-Sec	Activity, in curies $t^{-1.2}$	Energy, in Calories	Grams Fissioned
Criticality Incidents	3.0×10^{16}	1	3.0×10^{6}	2.4×10^{5}	1.6×10^{-5}
SL-1	1.5×10^{18}	50	1.5×10^{8}	1.2×10^{7}	8.0×10^{-4}
Borax	4.0×10^{18}	135	4.0×10^{8}	3.2×10^{7}	2.1×10^{-3}
Chalk River	1.2×10^{20}	4000	1.2×10^{10}	9.6×10^{8}	6.3×10^{-2}
Chemical Incident	---	---	---	1.0×10^{10}	---
20 KT Bomb	2.6×10^{24}	8.64×10^{7}	2.6×10^{14}	2.1×10^{13}	1.0×10^{3}

Therefore, at the end of approximately 1 day (8.64×10^4 seconds) or 10^5 seconds, the activity is reduced to $(10^5)^{-0.2}$ or 1/10 of the activity at 1 second. The values of long lived Sr^{90} and Kr^{85} activities under various operational conditions are presented in Table 2.

III. CLASSIFICATION OF REACTOR OPERATIONS

For purposes of hazard analyses, reactor operations may be classified as critical assembly operations or power level reactor operations. Critical assemblies are reactors that are operated at approximately zero power levels for relatively short periods of time. For all practical purposes, there is no build up of long lived fission products in a critical assembly. The activity generation in a critical assembly incident is given in Table 2 and this activity is characterized by a decay rate of $(t_2/t_1)^{-1.2}$. Power level reactors are operated for extended periods of time during which long lived fission products accumulate in the reactor core. This activity, which is a mixture of long lived activity, decays at the rate of $(t_2/t_1)^{-0.2}$.

IV. CAUSES OF CRITICAL ASSEMBLY AND REACTOR INCIDENTS

The causes or sources of nuclear incidents and the counter actions that may be taken are listed in Table 3.

The potential reactor incidents and the methods of preventing these incidents are presented in Table 4.

V. CONSEQUENCES OF CRITICAL ASSEMBLY AND REACTOR INCIDENTS

The possible consequences of critical assembly and reactor incidents are considerably different. A summary of these consequences is listed in Table 5.

VI. EMERGENCY PLANS TO REDUCE THE CONSEQUENCES

A. The probability and the consequence of a nuclear incident involving the uncontrolled release of significant activity in the environs can be markedly reduced by a systematic

Table 2. Summary of relationships of fission, energy and activity

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Basic Relationships

3×10^{16} Fissions = 1 Mw-sec
200 Mev/fission
$1.42\ (t_2/t_1)^{-1.2}$ Mev/sec/fission: Beta activity
$1.26\ (t_2/t_1)^{-1.2}$ Mev/sec/fission: Gamma activity
E_{avg} (Beta) = 0.4 Mev/dis
E_{avg} (Gamma) = 0.7 Mev/dis

Criticality Incident Relationships

3.0 $10^6\ (t_2/t_1)^{-1.2}$ (beta) curies Mw-sec
1.5 $10^6\ (t_2/t_1)^{-1.2}$ (gamma) equivalent 0.046 mcuries Sr^{90}/Mw-sec
0.022 curies 1-131/Mw-sec
0.046 mcuries SR^{90}/Mw-sec

Power Reactor Incident Relationships

$15 \times 10^6 \left[t_2^{-0.2} - (t_o+t_2)^{-0.2} \right]$ * curies (beta)/Mw at 1 sec
$9 \times 10^6 \left[t_2^{-0.2} - (t_o+t_2)^{-0.2} \right]$ curies (equiv. γ)/Mw at 1 sec
2.2×10^3 curies Sr^{90}/Mw at end of 1 yr operations
4.6×10^4 curies Sr^{90}/Mw at saturation
2.0×10^2 curies Kr^{85}/Mw at end of 1 yr operations
2.7×10^3 curies Kr^{85}/Mw at saturation

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*t_2 is the decay time in seconds after the incident
t_o is the operational period in seconds prior to the incident

development of the procedures set forth in Table 6.

B. The development of specific criteria to prevent or lessen the probability of an incident is of primary concern in emergency planning. In general, the factors expressed in Table 7 may be applied to prevent serious incidents.

C. Since the prevention of nuclear incidents of serious consequences cannot be entirely assured at this time even with the application of the factors set forth in Table 7, consideration must be given to the containment of a nuclear incident. The factors that should be considered in the provision of adequate containment of the radioactive materials are presented in Table 8.

D. The violation of the integrity of a container can be achieved through human error and equipment failures even though considerable efforts are taken to prevent such occurrences. Therefore, it is necessary to set forth plans for emergency action as listed in Table 9 such that the consequences of a release may be significantly reduced.

E. Following an incident wherein considerable activity has been released in the environs, there will be a need for damage control with respect to personal injury and property damage. A list of damage control factors is presented in Table 10.

F. The total plan to reduce the consequences and the probability of a nuclear release in the environs should include a system that is capable of integrating the data from all incidents, not only those experienced at the site in question, but also those experienced at other sites. Consequently, the following factors are set forth for the investigation of incidents in Table 11.

G. On the basis of the new evidence obtained from the analysis of the factors set forth in Table 11, a re-evaluation of the plans can be made to prevent the accident, to contain the activity, to act during the emergency, and to provide a method of damage control.

Table 3. Sources of and counter actions against nuclear incidents

Sources	Counter Actions
Inadequate design	1 Design reactor with inherently safe operational features. 2 Build in safety feature and provide adequate safety margin. 3 Design tests to assure safe conditions before operations. 4 Study causalities and accidents to which the nuclear plant may be subjected. 5 Verify the adequacy of design criteria by calculations and measurements. 6 Review the hazard summary report of the Advisory Committee on Reactor Safeguards.
Equipment Failure	1 Insert a fail-safe system. 2 Use a multiple channel system to provide effective back up of protective system. 3 Provide adequate, representative and proportional instrumentation to detect failures. 4 Use a built-in system for "go" or "no go" testing of equipment.
Human Error	1 Develop a method of adequate selection and placement for personnel. 2 Provide an effective training program for personnel. 3 Use appropriate and complete manuals of operation. 4 Define responsibility with singly directed supervision. 5 Apply a dual check system by operating personnel to reduce possibility of error.

Table 3 (Cont'd)

Sources	Counter Actions
Internal Forces	
Sabotage - (displeased employee)	1 Select carefully the personnel to operate the reactor. 2 Use effective security regulations.
Sabotage - (foreign agent)	3 Apply dual checking system by operating personnel thus requiring both persons to be involved in the plot. 4 Design system such that it is impossible for one person to sabotage the plant. 5 Organize and set forth procedures such that deviation from the normal is readily detected.
External Forces Earthquakes Tornado War damages	1 Review the history of the occurrences of earthquakes and tornado then take all reasonable care to design reactor facility to resist damage from these external forces.

Table 4. Potential reactor incidents and methods of prevention

Types of Incidents	Methods of Prevention
Directly Induced Nuclear Incidents	
Reactivity Incidents	
Start-Up	1 Limit rod rates. 2 Use of adequate multiple channel instrumentation. 3 Provide period and/or flux level scram. 4 Avoid positive temperature coefficient. 5 Insert a large neutron source in the reactor.
Cold Coolant	1 Install temperature difference interlocks to prevent an inadvertent injection of cold coolant into the reactor core. 2 Design reactor such that sufficient volume for coolant mixing is provided to limit the rate at which reactivity can be introduced. 3 Provide means to keep the coolant in the isolated loop warm. 4 Make available a flux scram.
Rod Jump	1 Design such that maximum shock does not cause rod to jump and increase the reactivity by an appreciable amount.

Table 4 (Cont'd)

Types of Incidents	Methods of Prevention
Directly Induced Nuclear Incidents Reactivity Incidents (Cont'd)	
Foreign Material Introduction	1 Design reactor in manner that virtually prevents the introduction of foreign material or detects presence before a significant incident can be incurred.
Shock Damage	1 Design against a significant shock.
Indirect Nuclear Incident Mechanically Induced Incident	
Loss of Coolant	1 Design such that coolant loop ruptures does not empty the reactor core coolant. 2 Use an emergency injection system to replace coolant. 3 Design system with adequate safety margin. 4 Test pressure vessel and loops to detect any possible source of loss of coolant.
Loss of Coolant Flow	1 Use multiple pumps and separate power supplies which are considered reliable. 2 Provide rapid means to detect loss of coolant flow and to scram in an adequate period. 3 Assure adequate thermal safety margin in design.
Control Rod Ejection	1 Complete casualty analyses and strengthen areas where control rod ejection may be probable. 2 Protect control drive mechanism by an adequate shield. 3 Provide assurance that a single casualty cannot eject all safety rods.
Chemically Induced Incident	
Metal-Water Reaction	
Gaseous Formation and Explosion	

Table 5. Possible consequences of critical assembly and reactor incidents

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Critical Assembly Incidents

Only localized on-site hazards are expected.
External radiation hazards are more significant than internal radiation hazards.
Rapid and temporary evacuation to a shielded area may be reqested.
No food problems are expected.

Reactor Incidents

Off-site hazards may occur.
Internal radiation hazards could be more significant than external hazards.
Lethal, illness, and greater than emergency maximum permissible exposures are possible.
Food problems may exist and persist.

Table 6. Procedures for reducing nuclear hazards

1 Prevention Planning (Safeguards)
2 Containment
3 Emergency Action
4 Damage Control
5 Incident Investigation
6 Reevaluation and Reapplication

Table 7. Factors of consideration to prevent nuclear incidents

Factors	
Pre-constructional Phase	Use radiological engineering safety concepts in the selection and design of the facility to include inherent and built-in safety.
Constructional Phase	Develop and use specific and adequate testing procedures and methods to assure quality control.
Pre-operational Phase	Develop operational procedures and review experiments. Make pre-operational inspections of the entire system.
Operational Phase	Make periodic inspection of equipment and experiments. Review all safety methods and devices in the light of current knowledge.
Administrative Phase	Develop clear and distinct lines of responsibility, authority and accountability. Designate responsible personnel for the continuing safety of the operation. Establish and use an objective review council with advisory responsibilities to the general manager or his counter part. Set responsibility for the intergration of the finding of the "Hazard Summary" type of report into the total emergency plan.

Table 8. Factors of consideration in containment

1 Assessment of Degree of Containment Required
2 Testing of Containment Vessel
3 Protection of the Integrity of Containment Vessel
4 Establishment of a Warning and an Alarming Exhaust System
5 Development of an Automatic Shut-down System
6 Consideration of Partial Containment
7 Use of Stand-by Filter Units
8 Use of Filter Units Within Container
9 Airlock Contamination and Release of Activity

Table 9. Emergency plan action factors

1 Design of an Effective Emergency Plan (Emergency Action System Kit)
2 Establishment of an Emergency Shut-down System (where desirable) for Neighboring Buildings
3 Establishment of Warning and Communication Systems
4 Development of Hazard Evaluation and Radiation Control System
5 News Release--Community Relations, etc.

Table 10. Damage control factors

1 External and Internal Monitoring of Personnel
2 External Decontamination of Personnel
3 Internal Decontamination of Personnel
4 Bone Marrow Therapy
5 Building Air Decontamination
6 Building and Equipment Decontamination
7 Area and Environmental Decontamination

Table 11. Incident investigation considerations

1 Review of all Incident Investigations of Particular Concern
2 Periodic Review of Incidents and Special Reviews
3 Establishment of Incident Review
4 Setting Forth of Objective Principles

VII. APPLICATION OF EMERGENCY PLANS FOR CRITICAL ASSEMBLY AND REACTOR OPERATIONS

A. For a reactor (critical assembly, research or power reactor) emergency plan, an Emergency Action System Kit (EAS Kit) can be developed. This EAS Kit should contain the following material:

1. Simplified color chart overlays on maps
2. Preliminary information data forms
3. Guide lines to estimate hazards
4. Maximum permissible levels
5. Meteorological data forms
6. Damage control data
7. Special information data form

B. The EAS Kit should Achieve the Following Goals:

1. Integrate all responsible personnel and agencies into a single and complete emergency plan.

2. Bring about an awareness of potential hazards and thereby set forth adequate safeguards to prevent the occurrence or lessen the consequences.

3. Increase the participation of cooperation of persons and agencies in the plan, thereby, eliminating the need for reliance on an individual who may not be available at the time of the incident.

4. Define clearly the basic data that should be obtained or supplied to the emergency information coordinator.

C. The EAS Kit should be developed by and with the cooperation of all responsible organizations and agencies. The Kit should integrate the information developed in the Hazard Summary Report into a form whereby an effective plan may be developed. The Hazard Summary Report should be the cornerstone for the development of the emergency plan rather than a means for obtaining permission to operate a reactor. Each person who has a responsibility in the emergency action should have an EAS Kit in his office readily available to his alternate in the case of need.

D. In the development of a critical assemblies emergency plan, the emergency action system will be influenced by the safety considerations that were given in the location and design of facility. It is highly desirable in the selection of the site that the air movement in the area be studied by the use of oil smoke bombs and fluorescent pigment particles, which are dispersed in the environs. These studies could yield information on the behavior of radioactive aerosol with respect to the possible intake into neighboring buildings. After the construction of the building additional studies could be conducted which may indicate information on the percentage of material released by a cell that may be taken back again into the building through the intake air system.

E. Initial preventive care should be taken to keep the population density in the reactor area at a relatively and reasonably low value. Such earlier action will reduce the possibility of confusion in the reactor area by the elimination of unnecessary and over crowded operations and reduce the number of potentially over-exposed personnel. Good radiological engineering will make the emergency action and evacuation plan a simple matter. A shielded passage way from the critical assembly area is desirable. Personnel should not be evacuated from a multi-office critical assemblies building unless it is clear that either significant quantities of activity have not been dispersed in the environs or that the exposures to persons who remain inside the building will be greater than the exposures that they would receive if they were evacuated.

F. Even through the initial dose rates from a critical assembly incident may be very high, the total exposures could still be very small. For example, a dose rate of 3,600 r/hr at 1 second after an incident would result in a total dose of 5 roentgens over a period of 1 second to infinity if neither the source nor the persons move. The above calculation is based on the characteristic physical decay of the short-lived fission products at a rate of $(t/t_1)^{-1.2}$. The time at which the exposure begins, t_1 is taken as 1 second. The time, t at which the exposure is terminated has maximum value of infinity. Experience has demonstrated that unless an effective emergency plan is formulated, almost all of the personnel will leave the building when the alarm is sounded, 50% will proceed from the building into the direction of the wind and into an area where the fission products may be dispersed in the air or deposited on the ground. The need for a single and effective plan wherein shelter is immediately taken is necessary. It should be noted that there is no time for delay in the case of a critical assembly incident. The activity decays rapidly, therefore, personnel must rapidly proceed to a shielded assembly area. There is no time for closing safes or securing materials.

G. In the design of the critical assemblies building, the emergency action plan can be simplified and the consequences of an incident markedly reduced if reactor cells are placed at favorable ends of the building at distances from the individual offices with equipment if necessary separating the cells from the offices. In general, it is recommended that air conditioning be used to eliminate the need for windows which may be open at the time of an incident. The location of air intake systems and critical assembly cell exhausts must be critically evaluated. The intake of large quantities of activity directly from the cell exhaust air following an incident must be avoided.

H. The rapid decay of the radioactivity associated with a critical assembly nuclear incident necessitates immediate or automatic action if any action at all is required. Since personnel may be in the immediate vicinity of the critical assembly area and since the exhausted material may be taken back into the critical assemblies building or adjacent buildings, it is desirable to have an automatic shut down exhaust system for each critical assembly cell and a system that automatically shuts down the intake fans in the area with possibly one or two exceptions. In some areas it may be more desirable to have a manual shut down since an automatic shut down could effect the release of serious concentration of radioactive or toxic materials from a hood into a laboratory area. These conditions should be completely evaluated to provide the most safe procedure.

I. With respect to the emergency action system, the following factors should be considered:

1. The need of a walkie-talkie communication system with central control.

2. The use of specified assembly areas to provide:
   a. Rapid analyses of the neutron, beta and gamma external exposures.
   b. Personal decontamination if necessary.

3. The application of signal lights and horns.

4. The integration of the fire department and security organization into the plan.

5. The development of the emergency plan during off-shift hours.

6. The indoctrination of sub-contractor employees into the emergency plan.

7. The periodic testing of the emergency action system.

J. In the development of a power reactor operational emergency plan, the following factors should be considered in an effort to provide an effective and complete plan.

Factors of Consideration for a Power Reactor

General Factor	Specific Consideration
. Prevention	1 Pre-operational environmental surveys will provide background data, legal information and aid in the establishment of good will in the community. 2 Plant layout should be such that an effective and timely evacuation plan can be readily achieved. Plant design should take advantage of the natural shielding offered at the site and the built-in shielding afforded by the structures on site. The placement of the parking lot in the predominately downwind direction of the site should be avoided.

General Factor (Cont'd)	Specific Consideration
Prevention	3 In the selection of the site, consideration should be given to the population density. Low population densities with virtually no or low growth potential are favorable factors in site selection. 4 The establishment of an advisory committee on reactor safeguards and the development of safeguards procedures should be initiated during the site selection phase.
Containment	1 The container should be designed to withstand rapid temperature and pressure charges induced by the maximum nuclear and chemical type incidents. The leakage of gases and activity from the container should be tested prior to reactor operations. The leak rate should be kept at the lowest possible value. The leakage from a well designed steel building can be maintained at a level of less than 0.1%/day. The leakage through electrical and service penetrations in a building may be 0.2%/day. 2 The automatic ventilation shut-down system can be provided which will operate on a fail-safe radiation detector system. 3 Adequate attention should be given to protect against the violation of the integrity of the container by a missile as a result of a nuclear and/or a chemical incident. 4 Stand-by air filter units in the exhaust system can be useful. It may be desirable to use a recirculating air cleaning system within or outside the building to collect the activity that may otherwise be dispersed within the building. 5 The use of an air lock system and the quantity of activity being released through large airlocks should be reviewed.
Emergency Action	1 Since the internal hazards can be significantly greater than the external hazards it is recommended that a sufficient number of light weight respirators with relatively high efficiencies be made readily available. 2 For power reactors, the evacuation plan should be developed with respect to the actual plant layout taking advantage of the natural and artificial shielding provided. It may be appropriate as such to wait for a brief period in a shielded area before evacuating the building and the area. 3 Aerial surveys should be made immediately following an incident to determine the extent of the hazard. 4 An EAS Kit should be developed.
Damage Control	1 Immediate and effective personal decontamination should be conducted. 2 Personal injury control may be achieved by hospitalization and conventional practices for exposures of 100 to 400 rem. Above 400

General Factor (Cont'd)	Specific Consideration
Damage Control	rem some consideration may be given to treatment by bone marrow transplants by experts. Analyses of blood samples will in time indicate the need or advisability of a transplant. 3 Personal exposures from the inhalation or ingestion of materials may be reduced by the use of chelating agents. 4 The hazards from the contamination of food products (milk, vegetables, etc.) can be reduced by the immediate stoppage of their sale from the areas wherein significant contamination has occurred. 5 Decontamination of the environs and the reactor building (if possible) should be considered.

VIII. CONCLUSIONS

In general, the following conclusions may be drawn.

A. To achieve the most effective and complete emergency plan the plan must be integrated into all operations from the time the site is first considered for potential selection.

B. Care can be taken to prevent the incident and to contain the fission products. These precautions will reduce the probability of the occurrence and lessen the consequences of an incident but they cannot eliminate these accidents and their effects. Therefore, it is necessary to provide an "Emergency Action System."

C. An Emergency Action System Kit can be developed which will be beneficial in the lessening of the consequences of an incident.

D. An Emergency Plan Review Committee should be established at each site with responsibility:

1. To make a general and scheduled yearly review of the existing emergency plans.

2. To call special meetings and to review incidents occurring at the site or similar sites.

3. To recommend improved emergency plans for the site.

The criteria set forth in this report can be the basis for the development of an effective emergency plan. The placement and acceptance of responsibilities in a clear and distinct manner in the emertency action system tend to reduce markedly the confusion and conflicts that might otherwise exist during an emergency. The development of an awareness about the consequences of an incident and the establishment of broad participation by responsible individuals in such a plan are important factors in the plan which will ultimately contribute to its success.

This lecture outline was prepared for Radiological Health Training Activities by Prof. J. J. Fitzgerald, Harvard School of Public Health, Boston, Mass.

Fission Product Inventories

I. INTRODUCTION

In case of an accident or other failure leading to the release of radioactive materials from a nuclear reactor, one of the first items required will be knowledge as to the amount of activity potentially available for escape -- that is, the inventory of radionuclides within the reactor. Since specific radionuclides vary widely in their chemical and physical characteristics, as well as their biological hazard, information on the quantities of selected radionuclides may be as important as knowledge of gross levels. The purpose of this lecture outline is to review computational methods for estimating gross and specific fission product inventories.

II. THE FISSION PRODUCTS

Nuclear fission yields a variety of products. These products, most of them radioactive (being beta emitters usually accompanied by gamma photons), are formed in definite proportions during the fissioning process. It is customary to refer to the proportion of a specific resulting radionuclide in terms of its fission yield For example, the fission yield of I^{131} is 3.1% and this represents the percentage of the fissioning fuel atoms which yield iodine of this mass number. Since the fission of each atom of fuel produces, for practical purposes, two fission product atoms, the total yield on this basis is 200 percent.

A. Decay Chains

Through emission of a beta particle, a primary fission product (or fission fragment) changes into a new nuclide representing a new element. This nuclide is often itself radioactive and it, in turn, decays, forming still another element with different chemical properties. Such sequential decay thus forms a chain made up of several elements formed serially, one from another, through successive beta-particle emissions, until an element is ultimately formed which is not radioactive. Although decay chains vary in length, each initial product is followed, on the average, by three decay steps before reaching final stability.

B. Decay Characteristics

A mixture of all the fission products exhibits decay characteristics which are a total of the complex of activities present. If the fission products (the short-lived as well as the long-lived) are formed at the same instant, as in the detonation of a nuclear-weapon, one type of decay pattern will be observed. If the fission products are the result of a sustained nuclear reaction, as in a reactor, a decay pattern of somewhat different nature will be observed. This is the result of the fact that in the latter case, during the time the reactor is in operation, new fission products are being produced concurrently with the decay of those already present.

For these reasons, the half-life of a particular radionuclide plays a prime role as to its relative significance in the inventory of radioactive materials within a nuclear reactor. In general, it can be observed that the longer the fission process is permitted to

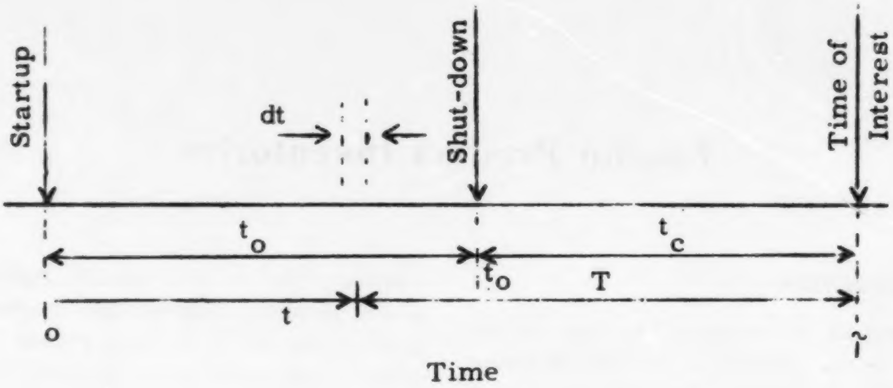

Figure 1

proceed (i.e., the longer a nuclear reactor has operated), the greater is the overall half-life of the total complex of activities. This increase stems from the fact that production over a period of time increases the relative proportion of the longer-lived products.

III. RADIONUCLIDE BUILDUP AND DECAY

There is a definite relationship between the power level of a nuclear reactor and its rate of production of radioactive fission products. Approximately 200 Mev energy is released in the fissioning of the nucleus of one uranium or plutonium atom. Using this value, it can be computed that a rate of 3.1×10^{10} fissions per second (or 2.68×10^{15} fission/day) is equivalent to a power level of one watt. On this basis, a one megawatt reactor utilizes the energy of only 1 gram of U^{235} per day.

A. Radioactivity of the Gross Mixture

Although the half-lives of the fission products range from a fraction of a second up to millions of years, it has been found that the decay of the gross mixture can be stated by means of a simple empirical equation.* This relationship, applicable from about 10 seconds up to several weeks after fission has occurred, is as follows:

$$\text{Curies per Fission} = 1.03 \times 10^{-16}\ T^{-1.2}$$

where: T = time after fission in days.

If a reactor is assumed to follow the operating procedure shown in Figure 1, then, using the above relationship, the inventory of gross fission products can be estimated.

t = total time since reactor start up;

t_o = length of time of reactor operation;

t_c = length of time of cooling, following shutdown;

dt = a small amount of time within the period of operation

T = decay time of fission products produced in interval dt (equal to $\tau - t$).

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*Probably accurate within a factor of two or less.

The number of curies of fission products after a time interval T, following a short period of operation, dt, and due to fissions occurring within this short period is:

$$dA \approx \left[1.03 \times 10^{-16}\ T^{-1.2}\ \text{Curies/fission}\right]\left[\frac{2.68 \times 10^{15}\ \frac{\text{fissions}}{\text{day}}}{\text{Watt}}\right]\left[P\right]\left[dt\right]$$

$$dA \approx 0.276\ P\ T^{-1.2}\ dt$$

where:

P = reactor power level in watts

dt = a small amount of time within the period of operation of the reactor

dA = activity of fission products produced during period dt.

The gross activity at some time, t_c, after shutdown of all the fission products produced during the entire period of the reactor operation is:

$$dA \approx 0.276\ P\ T^{-1.2}\ dt$$

$$T = \tau - t$$

$$A \approx 0.276\ P \int_{0}^{t_o} (\tau - t)^{-1.2}\ dt$$

$$A \approx 1.4\ P \left[(\tau - t_o)^{-0.2} - \quad {}^{-0.2}\right]$$

where:

A = number of curies

τ = time from reactor starting to time of interest

Since:

$\tau = t_c + t_o$

The equation can be written:

$$A\ (\text{Gross Activity}) \approx 1.4\ P \left[t_c^{-0.2} - (t_o + t_c)^{-0.2}\right]$$

The decay of the gross mixture of radionuclides after several periods of reactor operation is shown in Figure 2.

B. Radioactivity of Specific Fission Products

1. BUILDUP OF PRIMARY RADIONUCLIDES

The activity of a given fission product resulting from continuous operation of nuclear reactor at a given power level is a function of the fission yield and the half-life of the given radionuclide.

Neglecting neutron capture by the fission products, the activity can be computed as follows:

$$A_1^{t_o} = \frac{3.1 \times 10^{10}\ (P)\ (Y_1)}{3.7 \times 10^{10}}\ (1 - e^{-\lambda_1 t_o})$$

$$= (0.84)\ (P)\ (Y_1)\ (1 - e^{-\lambda_1 t_o})$$

where:

$A_1^{t_o}$ = activity of fission product #1 in curies at time t_o;

P = reactor power level in watts;

Y_1 = fission yield of product #1;

λ_1 = decay constant for fission product #1;

t_o = time of operation of the reactor;

3.1×10^{10} = fissions per second per watt;

3.7×10^{10} = disintegrations per second per curie.

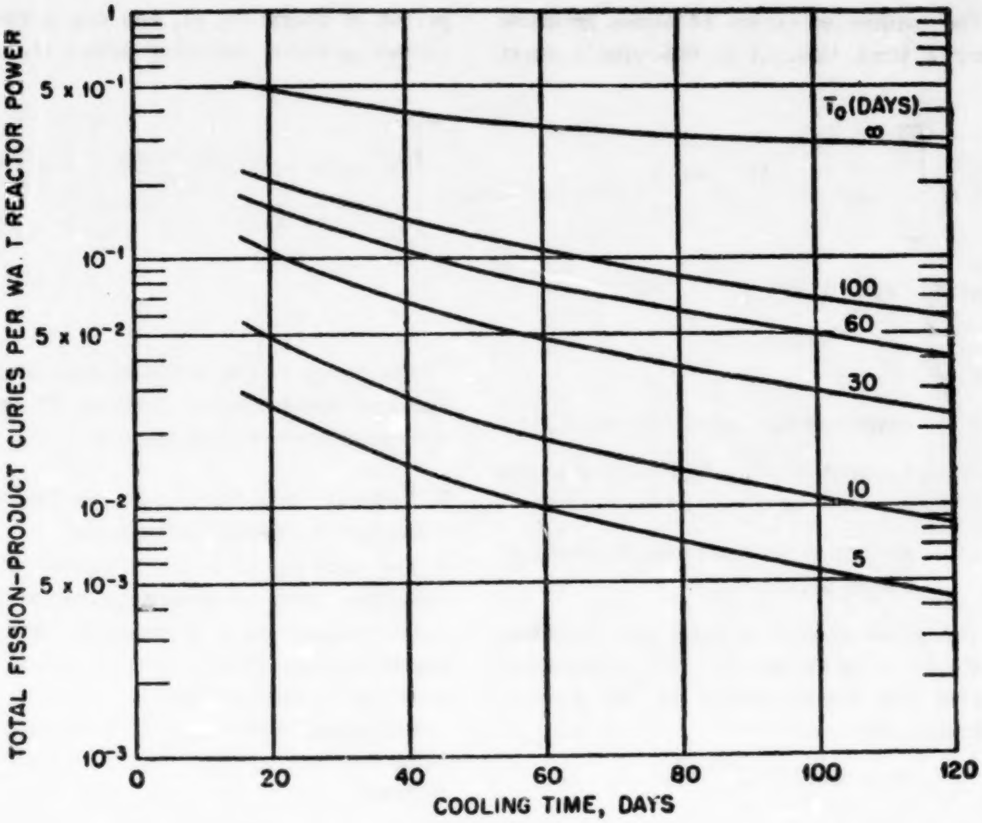

Figure 2.--Activity of Fission Products in Natural-Uranium Fueled Reactor

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2. BUILDUP OF DAUGHTER PRODUCTS

The rate of production of a daughter product (#2) of a given primary fission product (#1) can be calculated as follows: where the symbols follow the scheme previously designated.

It is to be noted that both following equations take into consideration the decay of each specific radionuclide while the reactor is operating and production is continuing. Typical quantities of specific fission products resulting for three selected reactor operating times are given in Table I. These data include figures for products resulting from the decay of daughter products of primary fission radionuclides. Because of the complexity of the equations for such calculations, they are omitted from this outline.

Table 1.--Production of Important Fission Products in a Reactor

Fission Product	Activity (Curies) after selected periods of continuous operation of a reactor at a power level of 1,000 kilowatts		
	100 days	1 year	5 years
Kr - 85	53	191	818
Rb - 86	0.25	0.26	0.26
Sr - 89	28,200	38,200	38,500
Sr - 90	402	1,430	6,700
Y - 90(a)	402	1,430	6,700
Y - 91	34,800	48,900	49,500
Zr - 95	32,900	49,200	50,300
Nb - 95(90 H)(a)	446	687	704
Nb - 95(35 D)(a)	20,900	48,200	50,500
Ru - 103	25,100	30,900	31,000
Rh - 103(a)	25,100	30,900	31,000
Ru - 106	753	2,180	4,220
Rh - 106(a)	753	2,180	4,220
Ag - 111	151	151	151
Cd - 115	4.8	5.9	5.9
Sn - 117	83	84	84
Sn - 119	< 24	< 64	< 100
Sn - 123	4	9	10
Sn - 125	100	101	101
Sb - 125(a)	12	43	139
Te - 125(a)	5	34	136
Sb - 127	787	787	787
Te - 127(90 D)(a)	146	260	277
Te - 127(9.3 H)(a)	808	922	939
Te - 129(32 D)	1,410	1,590	1,590
Te - 129(70 M)(a)	1,410	1,590	1,590
I - 131	25,200	25,200	25,200
Xe - 131(a)	250	252	252
Te - 132	36,900	36,900	36,900
I - 132(a)	36,900	36,900	36,900
Xe - 133	55,300	55,300	55,300
Cs - 136	52	52	52
Cs - 137	300	1,080	5,170
Ba - 137(a)	285	1,030	4,910
Ba - 140	51,500	51,700	51,700
La - 140(a)	51,300	51,700	51,700
Ce - 141	43,000	47,800	47,800
Pr - 143	45,000	45,300	45,300
Ce - 144	9,860	26,700	44,000
Pr - 144(a)	9,860	26,700	44,000
Nd - 147	21,800	21,800	21,800
Pm - 147(a)	1,290	4,900	16,000
Sm - 151	9	37	175
Eu - 155	23	74	207
Eu - 156	108	109	109
TOTAL	563,691	693,573	767,547

(a) Daughter product.

$$A_2^{t_o} = \frac{3.1 \times 10^{10} (P) (Y_1)}{3.7 \times 10^{10}} \left[\left(\frac{\lambda_2}{\lambda_2 - \lambda_1}\right)\left(1-e^{-\lambda_1 t_o}\right) - \left(\frac{\lambda_1}{\lambda_2 - \lambda_1}\right)\left(1-e^{-\lambda_2 t_o}\right)\right]$$

$$= 0.84 \; P Y_1 \left[\left(\frac{\lambda_2}{\lambda_2 - \lambda_1}\right)\left(1 - e^{-\lambda_1 t_o}\right) - \left(\frac{\lambda_1}{\lambda_2 - \lambda_1}\right)\left(1 - e^{-\lambda_2 t_o}\right)\right]$$

where the symbols follow the scheme previously designated.

The decay of the various radionuclides making major contributions to the gross mixture of fission products is shown in Figure 3, and Table II. The plotted data are based on conditions following operation of a reactor for an extended period of time. The data in the Table are for several selected periods of reactor operation.

3. DECAY OF SPECIFIC RADIONUCLIDES

Equations have also been formulated for following the decay of primary fission products and their daughter radionuclides after shut-down of a nuclear reactor.

The decay of a primary fission product may be calculated as follows:

$$A_1^{t_c} = A_1^{O} (e^{-\lambda_1 t_c})$$

where:

$A_1^{t_c}$ = activity of fission product #1 in curies after time t_c;

A_1^{O} = activity of fission product #1 in curies at reactor shut-down;

λ_1 = decay constant for fission product #1;

t_c = time since reactor was shut down (i.e., cooling time)

4. DECAY OF DAUGHTER PRODUCTS

The decay of a daughter product (#2) following reactor shut-down may be calculated as follows:

$$A_2^{t_c} = \frac{\lambda_2 A_1^{O}}{\lambda_2 - \lambda_1} (e^{-\lambda_1 t_c} - e^{-\lambda_2 t_c}) + A_2^{O} (e^{-\lambda_2 t_c})$$

IV. CONCLUSION

From the equation and curves given the fission-product inventories for reactors of any power level operated for different periods of time can be predicted. This information is valuable in reactor operations and also for predicting the quantities of wastes that must be disposed of.

One of the important facts that these equations and graphs illustrate is the initial rapid decline in activity of the fission products after removal from the reactor. A large percentage of the products quickly decay to stable states. In about 32 seconds the activity is one-half the activity at 1 second. In fact, after about 150 days, only 15 basic groups remain. After a period of about 2 years, only 9 groups remain. Thus, the aging process is, during this initial period, an important contributing factor to the solution of the problem of disposition.

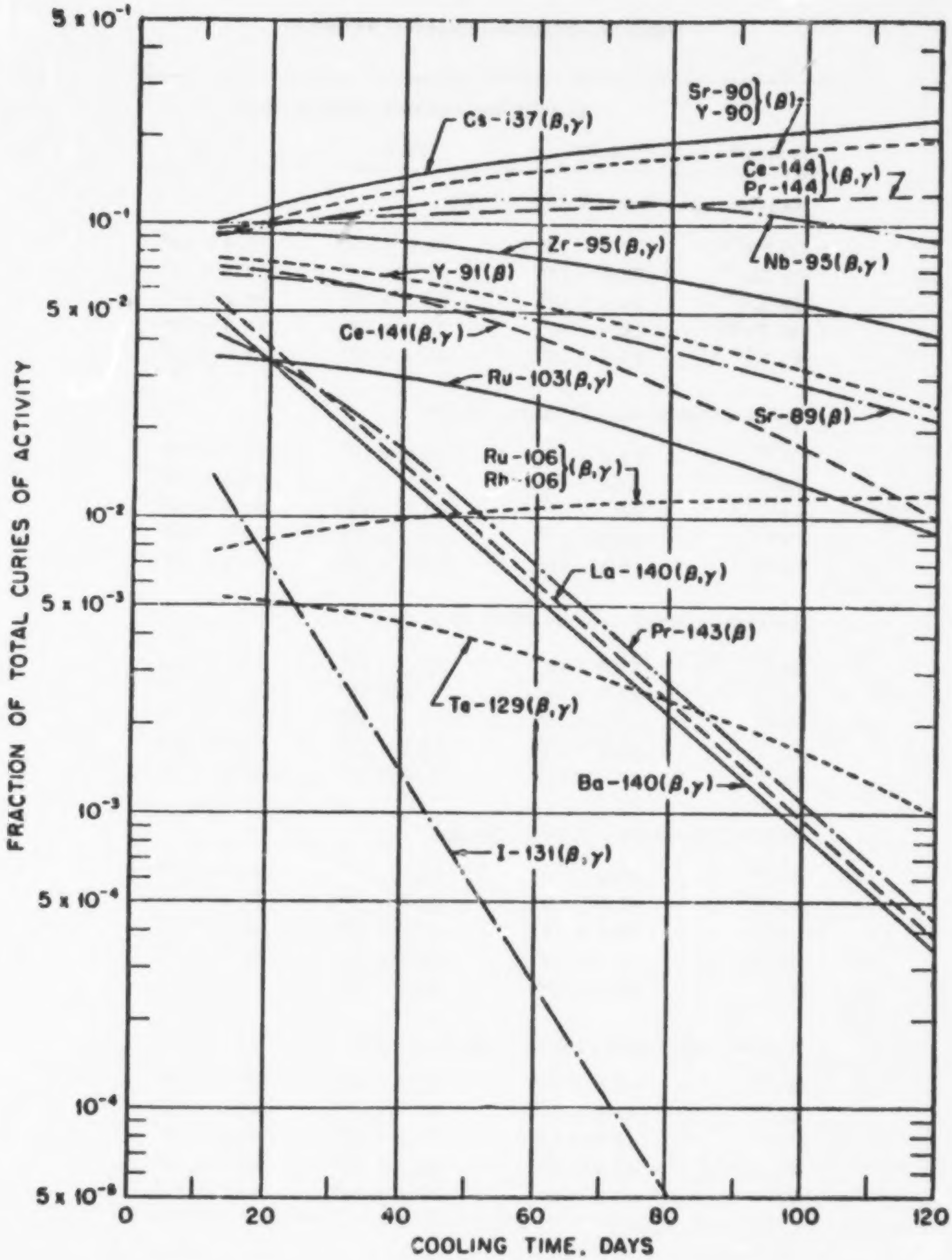

Figure 3.--Decay of Specific Radionuclides in Fission Product Mixture

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Table II.--Significant Reactor Activities

	Curies for various cooling times		
Isotope	6 hr	24 hr	48 hr
Reactor operation—1 day, 50 Mw			
(1) Xe^{133}	57.5×10^4	52.0×10^4	45.6×10^4
(2) Ba^{140}	24.8×10^4	23.5×10^4	22.2×10^4
(3) La^{140}	24.8×10^4	23.5×10^4	22.3×10^4
(4) Pr^{143}	24.0×10^4	23.0×10^4	21.8×10^4
(5) I^{131}	17.2×10^4	16.1×10^4	14.8×10^4
Reactor operation—21 days, 50 Mw			
Xe^{133}	44.3×10^5	40.0×10^5	35.0×10^5
Ba^{140}	33.2×10^5	31.8×10^5	30.5×10^5
La^{140}	33.2×10^5	31.8×10^5	30.5×10^5
Pr^{143}	32.2×10^5	30.0×10^5	28.4×10^5
Ce^{141}	19.4×10^5	18.8×10^5	18.4×10^5
Reactor operation—6 months, 50 Mw			
Ba^{140}	49.0×10^5	47.0×10^5	45.0×10^5
La^{140}	49.0×10^5	47.0×10^5	45.0×10^5
Ce^{141}	48.6×10^5	47.2×10^5	46.2×10^5
Pr^{143}	48.0×10^5	46.2×10^5	43.7×10^5
Xe^{133}	47.0×10^5	42.6×10^5	37.5×10^5
Reactor operation—1 year, 50 Mw			
Ba^{140}	49.0×10^5	47.0×10^5	45.0×10^5
La^{140}	49.0×10^5	47.0×10^5	45.0×10^5
Ce^{141}	48.6×10^5	47.2×10^5	46.2×10^5
Pr^{143}	48.0×10^5	46.2×10^5	43.7×10^5
Y^{91}	47.4×10^5	46.8×10^5	46.2×10^5
Reactor operation—1½ to 3 years, 50 Mw			
Ba^{140}	49.0×10^5	47.0×10^5	45.0×10^5
La^{140}	49.0×10^5	47.0×10^5	45.0×10^5
Ce^{141}	48.6×10^5	47.2×10^5	46.2×10^5
Pr^{143}	48.0×10^5	46.2×10^5	43.7×10^5
Y^{91}	47.8×10^5	47.3×10^5	46.7×10^5

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A Consideration of Combined Injuries Resulting from Nuclear Explosions

A study of the experimental work available, and our best clinical judgement to answer the following questions.

1. Disucss the current status of our knowledge of the effect of combined injuries, including blast, thermal, and nuclear radiation.

2. Estimate the morbidity and mortality responses that might be expected from varying degrees of each of the injuries in combination with the others.

3. Does the relationship of the time of radiation make a difference when considering ultimate blast and thermal response?

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Major, USA

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INTRODUCTION

Injuries resulting from the detonation of atomic devices are usually described as thermal, blast, and radiation effects. Casualties from each effect are usually discussed as distinct entities, with little or no comment as to the possibility of combination injuries. Obviously combined injuries will not be uncommon. Experience in the two Japanese cities indicates that combination injuries occurred in 40 percent of the 20-day survivors.

Important considerations in determining types of injuries produced will be such factors as type and size of weapon use, location of individual with respect to weapon, height of burst, pertinent geography and weather, amount and type of shielding present, and whether the victims present a trained or untrained, warned or unwarned, urban or rural population.

In some instances, shielding might minimize thermal and blast effects, whereas damage from neutrons and gamma radiation might be most significant in that order. Blast effects in an open field in terms of lethal primary envelope and translation envelope would be minimal when contrasted with the ranges of thermal and radiation damage. In a lightly constructed city, this would not be true as overpressures as low as 3 psi would cause many severe lacerations from flying glass and other debris. Many fractures, crush injuries and burns from secondary fires would result from collapse of buildings.

Weapon design, size and location of burst influence the character of injuries soon. Surface bursts increase the fallout and residual radiation hazard. The thermal and blast patterns of large devices overshadow initial radiation. The converse is true in the case of certain small weapons where radiation becomes the dominant factor.

With respect to all types of injuries, the psychological effect of "that which can neither be seen nor heard while it destroys,--not immediately, but after days of uncertainty--causes panic, depression, and illness." It is felt that this emotional factor can hardly be overestimated in any consideration of management of nuclear warfare casualties, both as a primary cause of illness and as a cause of delayed recovery from other injuries.

In the following presentation, we shall first briefly outline the elements of our knowledge of each effect individually. Then various combinations of injuries will be considered on the attached chart. This chart is designed to consider all three of the questions of our problem. Patients will be considered as having received optimum treatment, hence direct application of these opinions to a mass casualty situation is not possible, except as an aid to triage. Since little information relating to combined injury was found in the literature, conclusions listed often represent the combined opinions of the authors based on their own clinical experience and the information that was available to them.

BLAST INJURY

Direct Blast Injury: Very few primary blast injuries of significance were seen in Japan and this would probably be true in any future nuclear disaster. Direct blast injury includes ruptured eardrums, internal visceral damage such as pulmonary hemorrhage, ruptured large bowel, liver or spleen. It also includes vertigo, tinnitus, headache, and some instances of temporary loss of consciousness. No lesions in the lung or intestines were found in the Japanese that were the result of direct blast injury. Ruptured ear drums occurred in less than 1 percent of casualties in the Japanese cities. It is considered that, in general, a 35 psi static overpressure would be necessary to produce significant primary blast injury, and 100 psi necessary to kill directly. At any range permitting such overpressures, the accompanying thermal and radiation injury would almost certainly be lethal except under extraordinary circumstances in a shelter near GZ which shielded an individual from radiation and thermal effects, but not blast. Such a shelter might be a concrete wall or small hillock which gave a shadow shield for thermal and radiation.

In general, then, we will not encounter primary blast injuries in significant numbers.

Indirect Blast Injury: Injuries caused by flying debris, a victim's being thrown by the blast against another object, falling buildings, and by fires started in these collapsed buildings are considered indirect blast injuries. Burns from these secondary fires are not considered in this section. Typical secondary blast injuries include simple and open fractures, penetrating abdominal and chest wounds, amputations, multiple lacerations, visceral trauma, vascular injuries, severed tendons, ocular and CNS injuries. Particularly devastating in Japan were the flying glass particles, both small and large. Many patients were encountered with scores of small but deep glass wounds which permitted rapid exsanguination and early death from shock without treatment. Infected and delayed recovery due to radiation were frequent in this type of wound. Although fractures were seen in only 2-3 percent of survivors (many having died in fires), even this small percentage taxed medical facilities heavily. Flying debris was the number one cause of non-fatal blast injury. Glass was commonest offender. Fatal blast injuries were mainly in the zone of complete destruction. Within 3.1 miles of GZ, the incidence of blast injury was 82.8 percent in Hiroshima, and 71.6 percent in Nagasaki. Tetanus and gas infections were unusual complications in Japanese experience. Other types of infection, however, along with diminished resistance, increased bleeding tendency, fluid and electrolyte disturbances from radiation were important complicating determining factors in increased morbidity and mortality in Japan.

Combined mechanical injuries in Japan were noted in this frequency:

Mechanical plus radiation	13.4%
Mechanical plus burns	4.2%
Radiation plus burn plus mechanical	3.8%

Detailed consideration of selected combined injuries, including those due to blast, will be found on the attached chart.

Certain impressions are perhaps worthy of mention. It was felt that the combined blast and radiation injury, depending upon timing and upon degree of the respective injuries, presents several problems:

Radiation victims do not tolerate surgical procedures, manipulation of fractures, and other "shocking" procedures such as anesthesia, debridement, or grafting well. Due to leucopenia, malnutrition, and electrolyte disturbances, delayed wound healing and infection would be major problems. Treatment of shock would be complicated by nausea, vomiting, diarrhea, anemia, and bleeding tendency. Injuries occurring several days after significant radiation, that is during the phase of platelet depression and increased capillary fragility, might well result in serious or fatal internal or external hemorrhages. Surgery would be complicated by bleeding, delayed healing and infection. Contamination of wounds with plutonium or other internal emitters is possible, but not likely to be seen often. Treatment of patients with fractures of long bones, vertebrae, skull, and pelvis is going to be complicated by radiation diarrhea and vomiting alone, not to mention the other radiation effects.

Blast injury and burns combined also present problems in that surgical treatment of wounds will be complicated by having to operate through a burned area, orthopedic casting is most difficult over a significantly burned extremity, shock from burns will be increased by blast injuries and necessary treatment, and the problem of infection in a wounded and burned patient is even worse. The Brooke Army Medical Center burn unit experience stresses the advisability of avoiding surgery on severe burn cases as healing is extremely poor, even in the absence of radiation injury.

The unfortunate individual with burn, blast and radiation injury presents all possible combinations of the previously described complicated factors.

RADIATION

Our information regarding the morbidity and mortality which would result from the radiation effects of nuclear warfare is based on the experiences of the Japanese at Hiroshima and Nagasaki. Some additional information is available from the accidents at Los Alamos. The medical use of ionizing radiation contributes a slight amount of knowledge. All of our direct experimental work must be extrapolated from our work with experimental animals. This is extremely difficult to do with reliability because of the wide variation in the LD-50 for different animals.

The medical use of the X-ray gives us an idea as to what constitutes the radiation syndrome. However, in all cases this is complicated by the fact that the patient also has a malignancy. In medical usage, the dose is limited to a small area, seldom more than 600 cm^2 of body surface per day. Furthermore the dose is fractionated over a period of several weeks.

However, the recent work of Dr. Vincent Collins in which he delivered as much as 200 r total body irradiation in a single dose to patients is of importance to us. He reported no significant morbidity in these individuals.

The Los Alamos accidents resulted in two deaths. The estimated whole body dose was 590 r to the first patient. However, another complication is that the patient received an estimated 20, 000-40, 000 r to his right hand. We know that he became nauseated within 1-1/2 hours after exposure and vomited intermittently for 24 hours. He felt relatively well from the third to the sixth day, but died on the twenty-fourth day.

The second victim received an estimated 200 r whole body dose. He also exhibited early nausea and vomiting followed by a period of several days during which time he felt relatively well. He died on the ninth day.

At the time of the Los Alamos accidents, several individuals received smaller amounts of radiation. One worker received about 415 r. He vomited once within 12 hours, but never became critically ill. There was also a period of weakness. After 32 months he had developed a cataract. The remaining exposed individuals received doses ranging up to 200 r. None of them suffered any ill effects.

Definite conclusions as to what represents an LD-50 based on Japanese bombing is difficult. The investigators felt that the deaths which occurred at distances of about one mile from the hypocenter resulted from flash burns. About 80-85 percent of the unshielded died at these distances. Many of the deaths from radiation were among those who were shielded against the flash burn but only poorly shielded against the gamma (and neutron) radiation. LD-50 estimates based on this data have ranged from about 400 to 700 r.

The Japanese data concerning the clinical syndrome of radiation sickness is the same as that demonstrated by the Los Alamos studies. Nausea and vomiting is the earliest symptom and is usually closely related to the severity of the radiation. Epilation usually occurred within one to four weeks. Purpura occurred about as often as epilation. The peak of the purpura is between the sixteenth and the twenty-second day. The hemorrhages are most common in the upper half of the body. Associated with their onset, there is an increased tendency to bleed from lacerations, fractures, and burns.

Following severe radiation, the lymphocytes drop immediately and reach their low point in about five days. A few days later the granulocytes begin to drop and about the same time the lymphocytes begin to recover.

It must be admitted that we have little to offer in the way of specific therapy for acute radiation illness. Immediate hospitalization with proper sedation is beneficial. The maintenance of water balance is important since these patients are nauseated, vomit, and develop diarrhea. Blood transfusion may be necessary. Infections will develop as the white count falls, and the use of antibiotics is recommended along with transfusions as indicated. Any consideration of the therapy of radiation illness must take into account the fact that many cases will be complicated by flash burn and blast injuries.

BURNS

Burns, alone and in combination with other effects, will be our most difficult casualty care problem. The proportion of burns, to other effects, will depend upon the type of detonation, shielding, and whether in the open or in city type terrain.

Under optimum care, we will require a mountain of supplies for each burn case of 40 percent total body area. This would include up to 42 tanks of oxygen, 3 nurses, 40 pints of whole blood, 36 pints of plasma, 100 pints of other fluids, 2.7 miles of gauze, and other miscellaneous supplies such as M.S. and antibiotics. One physician will probably be able, under ideal conditions, to care for 1 to 4 burn areas.

In our evaluation of the Japanese bombings we find that thermal was the leading cause of death (50 percent), with radiation injury second at about 30 percent, and blast was the least lethal with only 18 percent of the deaths. 40 percent of the casualties had multiple types of injuries. An important factor influencing the death rate in multiple type injuries was ionizing radiation. The effect of ionizing radiation not only complicated the shock picture in early phases, but about the second to fourth week there was a secondary increase in deaths as the effect of radiation on resistance to infection potentiated the lethality of certain injuries. Both flash and flame burns responsible for death on the day of the bombing, but their relative proportion is unknown. In those 20-day survivors studied by ABCC, over 90 percent of the burned survivors had flash burns, and only a few percent had flame burn.

Type of cases: Our burn cases will be divided into two types; flash burns and secondary fire burns. The flash burns, in general, will cover less than 35 percent of the body area, but may go up to 50 percent of the body area, as they are burns of the profile type. Fire burns, or secondary burns, may be caused by clothing ignition from the flash burn or they may be sustained in fire storms following bombing. The flame burn is the same as any other flame burn seen in military or civilian practice. The flash burn is unusual only in that it is of profile type and occurs in a very short time. Two points were noted in the Japanese flash burns, 1) there was an immediate (within 10 min.) production of bullae in the majority of cases, and 2) flash burns appeared to cause a deeper pigmentation effect than flame burns.

In the Japanese bombings, over 70 percent of all deaths occurred within the first day, and of these more than 50 percent were due to thermal injuries. It was noted in the 20-day survivors that the majority of burns were less than 10 percent of body burn area, but a considerable number were from 10-20 percent, and only an occasional case of more than 40 percent surface area burn. From this we might deduce that the LD-50 would be around 30 percent of body surface burn, and the LD-90 about 40 percent body surface burn. This is contrasted with the peace-time LD-15 of

50 percent, LD-90 of 70-80 percent, and LD-100 of greater than 80 percent body surface burn.

Radiation sickness will be one of the complicating factors in burn cases from tactical use of nuclear devices, whereas in strategic bombing of cities the blast will complicate the burn picture. In the Japanese bombings, burn healing followed the usual course except where it was complicated by infection, malnutrition, or the systemic effects of the radiation. About the second to fourth week the effects of radiation show up in the body's ability to fight infection and at this time sublethal burn cases may succumb due to the additive effect of radiation.

If we take a moderate burn and add it to the insult of 100 r whole body radiation we jump from the two sub-lethal doses into a lethal range. Burn and radiation effects can be considered to be more than just additive. An LD-50 from radiation plus an LD-50 from burns would be an effective LD-50, in fact you would be "overkilling". In breaking this down we can consider the following:

Burn (point system)	Radiation	Lethality
Less than 10 points	LD-50	LD-50
10-25 points	LD-50	LD--60-70
25-35 points	LD-50	LD-80
35-45 points	LD-50	LD--90-100
Greater than 45 pts.	LD-50	LD-100
20 points	SD-50	LD-20
20 points	LD-20	LD-40
20 points	LD-50	LD-70
20 points	LD-70	LD-95

Only a few studies from the Japanese bombings which have been released to the general public have had any indication of the combined effects of thermal and radiation.

Therapy: To adequately treat burn casualties, particularly in mass casualty work, we must have some method of prognostication. The rule of nine is used to estimate per cent of body area burned. Pillsbury, following the Brooke Army Medical Center plan, has suggested the following index; (this index issued in the above table).

Points are given on the severity of the burn and also for each per cent of body surface burned. On the basis of this the LD-50 (for pure burn) was established as 45 points, no matter how attained. For each percent of body area of third degree burn we give one point, and for each percent of second degree burn we give one half-point. Thus if we had 20 percent third degree, and 40 percent second degree burn we would have an index of 20 plus 40/2 for a total of 40, or almost an LD-50. In a mass casualty situation we arbitrarily say that a casualty with greater than 40 percent burn should be treated expectantly, with less than 15 percent burn should be self care, and the group with 15-40 percent should receive our greatest effort. Naturally the effects of radiation will complicate this picture. A good point to remember is that a casualty from tactical weapon detonation, with third degree flash burn under his clothing will have received an LD-100 from radiation.

Flash burns have one advantage over flame burns in their treatment, and that is that not more than 50 percent of the body surface is burned, and the remainder of the surface can be used for treatment (fluids, etc.) and as an un-affected area for the patient to lie upon. If we have such an unaffected area for the patient to lie upon we can use open treatment to advantage.

In a rat experiment using a burn which gave 10 percent mortality, it was shown that by adding 100 r it would give 74 percent mortality. The 100 r alone gave no mortality. Now if the animal was given the burn plus 100 r plus penicillin the mortality was reduced from 70 percent to 14 percent. This would tend to show antibiotics would be advantageous in therapy of burns. In some human studies antibiotics have proved very beneficial even though no infection was found in the burn or in the blood culture. There seems to be some evidence that in spite of these negative cultures there is infection somewhere in the body which is slowing the healing process, if we get rid of this infection the healing rate increases.

Our first, and primary concern, in a burn patient is with resuscitation. If we cannot resuscitate a patient we naturally cannot go on to debridement and follow-up.

In resuscitation one of the main problems is maintaining an airway. A patient with a second degree burn of the face and neck can be expected to have considerable edema by the second day, and almost invariably will need an emergency tracheotomy. It is much better to do a tracheotomy prior to the onset of edema. Most of the flash burns of the Japanese bombings were of the extremities, head, and neck variety; and we can expect little difference from our battlefield burns. The exposed skin is the part most affected, particularly the skin around the eyes is most sensitive to thermal effects.

Fluid and electrolyte balance is the second most important part in resuscitating a burn patient. The Brooke Army Medical Center fluid formula is easy to remember and gives the patient adequate fluid. One must beware in estimating the percent burned, even if the patient has more than a 50 percent burn, never use more than 50 percent for calculating fluid requirements or you will drown the patient. Below are for a "standard man".

During the first 24 hours (1/2 within first 8 hours):

0.5 cc. of colloid/kg / percent body area burned

1.5 cc. of electrolytes /kg/ percent body area burned

2000 cc. of glucose in water

During the second 24 hours:

Colloid and electrolytes to 1/2 the amount of first day.

2000 cc. of glucose in water.

After 48 hours:

Give predominately water. Maintain the serum sodium level at about 135 meq/liter, and keep the hematocrit about 45. Give 80-120 meq of potassium per day.

As long as the urine volume is maintained at about 30 cc./hour you know you are doing o.k. with the fluids.

The best electrolyte solution is lactated Ringer's and Poly-sol. Saline solutions are a poor second. Blood, plasma, and dextran, in that order, are good colloids. It must be remembered that the effects of ionizing radiation can also cause a retention of fluid and thus possible pulmonary edema.

The oral route for fluids and electrolytes is to be preferred whenever practical. A good oral electrolyte solution can be made up of 3 grams (1/2 teaspoon) of NaCl (salt), and 1.5 gm (1/2 teaspoon) of soda bicarb per a quart of water. If this is chilled and has a little lemon or lime juice added to it we have a good, though somewhat distasteful, oral electrolyte fluid.

Certain cases, undoubtedly, will have to receive debridement. If possible, we would advise a non-surgical type of debridement in which enzymatic action of certain solutions from clostridium histolyticum cultures are applied to the burn area. This enzymatic action has a dissolution effect upon the dead collagen. If it is decided that surgical debridement is preferred, then the best time to do such debridement would either be immediately, or after the fourth week. If done immediately the effect of the radiation will not be so pronounced as it would be during the second to fourth weeks; after the fourth week the effect of the radiation diminishes and the burns (or surfical wounds) again heal more rapidly. It must be remembered that in the severely burned and in the irradiated casualty, wound healing (such as in debridement) is very much depressed. It has been shown, that burns sustained in the Japanese bombings did not heal even four months after the blood picture returned to normal. In the optimum treatment of burns; immediate debridement can be followed by skin grafting in a few days; whereas if the open treatment is used it may be three weeks or more before the third degree burn sites are ready for skin grafting.

To keep down infection, one should start on a prophylactic antibiotic program. The choice of antibiotics is left up to the individual physician. We feel that the treatment of choice is chloramphenicol in a dose of 250 mg four times a day. Most burn contaminants (staph haemolyticus, strep, and other less known ones) respond well to it.

One of the most important facets in good burn therapy is that of good nursing care.

If the closed method of burn therapy is elected, we should change the dressings at least every other day, and preferably once a day. The dressing should consist of a fine mesh gauze (some suggest the use of vaseline or furacin gauze) against the burn, then mechanics waste or cellulose batting, and finally a firm bandage to hold the rest in place.

Good burn and supportive therapy is also good radiation syndrome sickness therapy.

SUMMARY

In summary we feel that:-

1. Direct blast will not be a major cause of lethality in any significant number of casualties.

2. Injuries due to secondary effects of blast, i.e., flying glass and also secondary fires, may play a major role in additive injuries.

3. Handling of mechanical injuries should be with a minimum amount of additional trauma, and particularily if radiation injury also is involved.

4. Radiation victims do not tolerate surgical procedures, manipulation of fractures, and other "shocking" procedures such as anesthesia, debridement, or grafting well. Due to leucopenia, malnutrition, and electrolyte disturbances, delayed wound healing and infection would be major problems.

5. In radiation sickness, the physician should exercise his best clinical judgement in the use of sedation, fluid and electrolyte balance, transfusions, antibiotics, and good nursing care.

6. Burns will be our most difficult casualty problem.

7. Burn and radiation effects can be considered more than additive.

8. They will require enormous amounts of supplies for each burn case and will tie up more personnel then would any other type of casualty.

9. Good burn and supportive therapy is also good radiation syndrome therapy.

10. Adequate therapy should consider:

- a. Patent airway. (Tracheotomy early if indicated)
- b. Adequate fluid and electrolyte balance
- c. Prophylactic antibiotics
- d. Early debridement is preferred to late
- e. Good nursing care.

11. Mechanical injuries will not complicate a severe burn problem, but a severe (or even moderate) burn may complicate the mechanical injury problem.

12. A good point to remember is that following the detonation of a "tactical" size weapon, a casualty who received a third degree burn under his clothes from the weapon will also have received an LD-100 dose of radiation.

13. The additive effect of radiation on burns may be considered as resulting from one or more of the following:

- a. Initial shock of high dose radiation
- b. Dehydration due to nausea and vomiting
- c. Poor healing of burns in radiated areas.
- d. Depressed blood picture following radiation. This would lead to a much poorer resistance to infection.
- e. Depression of body's antibody formation by radiation.
- f. Electrolyte imbalance due to the nausea and vomiting.

Table 1.--Combined Injury Table--Percent Mortality

Additional injury	Radiation Injury								No Radiation
	Radiation followed by injury in--						At time of injury		
	One month		Two weeks		One week				
	SD-50	LD-50	SD-50	LD-50	SD-50	LD-50	SD-50	LD-50	
Compound fracture of femur	5	60	20	75	15	70	10	65	1.2
Head injury	50	75	70	100	65	100	75	100	46.0
Multiple laceration	5	60	15	75	10	65	5	60	2.2
Penetrating wounds of abd. & thorx.	20	70	25	95	20	85	50	90	10.3
15 pt. burn	7	60	20	70	15	60	20	65	5.0
30 pt. burn	30	70	40	80	60	80	60	85	25.0
45 pt. burn	55	85	90	95	90	100	90	100	50
Above fx + 30 pt. burn	50	80	60	90	65	95	85	95	45.
Above fx + 45 pt. burn	85	95	90	100	90	100	95	100	80
Above laceration + 30 pt. burn	55	85	70	85	65	80	75	85	50
Above laceration + 45 pt. burn	90	95	93	100	95	100	98	100	85
Penetrating Abd. or thoracic wnd plus 30 pt burn	95	98	100	100	100	100	100	100	90

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Radiation sickness is a symptom complex which may be divided into five groups:

General Symptoms: headache, vertigo, debility, abnormal sensations of taste or smell.

G.I. Symptoms: Anorexia, nausea, vomiting, diarrhea.

Cardiovascular Symptoms: Tachycardia, arrythmia, fall of BP, shortness of breath.

Hematologic Symptoms: Leucopenia, thrombopenia, increased rate.

Psychic Symptoms: Increased irratibility, insommnia, fear.

The Acute Radiation Syndrome in Man

George E. Thoma, Jr., M.D.[1] and Niel Wald, M.D.[2]

I. INTRODUCTION

Present knowledge of the effects of known doses of various radiations on normal humans is mainly indirect.

It comes from:

1) controlled experiments with mice, rats, rabbits, and monkeys in the radiobiological laboratory

2) analyses of findings in therapeutically irradiated sick humans

3) retrospective studies of accidental human radiation exposures

Several drawbacks are evident in these data.

1) Because of the variations in radiosensitivity of different tissues in different species, the controlled laboratory studies are not readily extrapolated to man.

2) The biological responses of recipients of therapeutic irradiation are not necessarily those of normal humans.

3) In accidental exposures of normal humans, detailed precise measurements of dose and uniform selection of test parameters and procedures have not always been possible.

Because of these drawbacks, it was deemed essential that certain medical guidelines be established for the management of cases of radiation overexposure, not only to facilitate the management of accidental clinical radiation injury in the individual patient, but also to expedite the accumulation of more useful data concerning such injury, as a basis for further improvement in its diagnosis and therapy.

To make maximum use of past experiences with radiation accidents in developing the guidelines for their future clinical management, all presently available data concerning human exposure from criticality accidents were reviewed.[3, 4] Only normal case material in which the radiation exposure was

acute
external
penetrating
generalized

was considered. The clinical syndromes resulting from various protracted, internal, superficial, and localized exposures were too varied for the purposes of our study.

In this lecture outline, the sequence of events and resulting personnel exposures of each accident will be reviewed and discussed. Following a discussion of the clinical manifestations of radiations of radiation injury, the symptomatology and laboratory findings of the victims of these accidents will be reviewed and analyzed. Certain recommendations for diagnosis and management will also be made based on the material reviewed.

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[3] Thoma, G. E., Jr., and Wald, N., The Diagnosis and Management of Accidental Radiation Injury, Journal of Occupational Medicine, 1:421, 1959.

[4] Wald, N., and Thoma, G. E., Jr., Radiation Accidents: Medical Aspects of Neutron and Gamma-Ray Exposures, ORNL-2748 Part B, Oak Ridge National Laboratory, 1961.

II. ANALYSIS OF PAST ACCIDENTS - PHYSICAL ASPECTS

Since the onset of widespread research and production activities in nuclear technology dating back to the inception of the Manhattan Project, there have been 7 major criticality accidents, involving significant overexposure to 31 persons, and 4 fatalities. These accidents are listed in chronological order in Table 1.

The characteristics of fissionable material vary with the mass and shape of the material. It is said to be "critical" when it is of such configuration that a nuclear reaction can be sustained at a fixed level of intensity. If the critical dimensions are exceeded, an exponentially increasing chain reaction will occur. Accidental excursions of this type produce variable intensities of fast neutrons and gamma rays. Accidents of this nature are referred to as criticality accidents. All of these accidents were of this type.

Since the time of the first of these accidents (16 years ago), there has been a continuous evolution and improvement in the techniques and concepts of radiation dosimetry. For example, dose units such as the gram-roentgen are no longer believed to be significant indices of radiation exposure, and

Table 1. Chronology of radiation accidents

Accident	Date	Type
Los Alamos I	Aug. 21, 1945	Criticality (Exp. assembly)
Los Alamos II	May 21, 1946	Criticality (Exp. assembly)
Argonne	June 2, 1952	Criticality (Reactor)
U.S.S.R.	1953 - 1955 ?	Criticality (Reactor)
Oak Ridge	June 16, 1958	Criticality (Processing)
Yugoslavia	Oct. 15, 1958	Criticality (Reactor)
Los Alamos III	Dec. 30, 1958	Criticality (Processing)

time has served to accentuate the complexity of the RBE concept. An effort was made to re-evaluate the dose assigned to certain individuals involved in nuclear accidents, using modern techniques of radiation dosimetry.

To put the physical dosimetry of past accidents on a common objective basis, the dose to a given individual is specified in terms of the absorbed dose (in rad), which would have been received by a small mass of tissue located at the position of the individual.

The method which has been found most reliable for evaluating the neutron dose to persons exposed in mixed radiation fields is the measurement of the amount of radioactive sodium (Na^{24}) which is produced when the neutrons interact with normal sodium (Na^{23}) in the body. It has been found that the first collision neutron dose to the body may be related in a simple way to the spectrum of incident neutrons as determined from threshold detector measurements.

Estimates of the gamma-to-neutron dose ratio are used to allow one to assign both gamma and neutron doses on the basis of Na^{24} activation in the body.

III. SUMMARY OF ACCIDENT AND EXPOSURE DATA

A summary of the accidents is shown in Table II. In columns 5, 6, and 7, the total body doses are listed as originally reported. The last 3 columns are the calculated doses based on modern dosimetry methods. They are all expressed in rad.

LOS ALAMOS ACCIDENT, LASL I

The first nuclear accident occurred at the Los Alamos Scientific Laboratory, Los Alamos, N. Mexico, on Aug. 21, 1945. In a criticality experiment involving a metal system, a nuclear excursion occurred and two persons were exposed to the mixed radiation field from this assembly. One of them (Case LA 1), who died after the accident, was touching the assembly when the chain reaction occurred and consequently received a very high dose to his hands and a smaller dose to the bulk of his torso. He was exposed to considerable gamma radiation from fission products while dismantling the experiment after the reaction took place and possibly would have survived had he left the room immediately. His actions during this period are not well known, and the total dose received is correspondingly uncertain. Neither he nor the other person exposed were wearing film badges at the time of the accident. Since the number of fissions which occurred in the assembly is not known accurately, the best index of his neutron exposure is the Na^{24} activity level in his blood. The neutron dose calculated from these data is 297 rad. The gamma dose is impossible to ascertain owing to the uncertainty of his whereabouts in the immediate postcriticality period. Therefore, his dose is given as 297 + rad.

LOS ALAMOS ACCIDENT, LASL II

The circumstances surrounding the second major radiation accident at Los Alamos, on May 21, 1946, were quite similar to those of the first accident. Personal film badge data were not available, and data from badges located on the walls of the room were not very helpful. Eight persons were exposed to significant doses in this incident. It is felt that none of these victims received uniform total body exposures because of various amounts of partial body shielding. One fatality occurred.

ARGONNE ACCIDENT

A reactor criticality accident occurred at the Argonne National Laboratory, near Chicago, on June 2, 1952. Four persons were

Table II

Summary of Exposure Data

Accident	Number Patients	Patient Code*		Reported Total Body Dose			Calculated Total Body Dose		Calculated*a Total Rad Dose
		R	L	Neutron	Gamma	Total	Neutron	Gamma	
LASL - I	2	LA1	1	480 rem*b	110 rem	590 rem	297 rad	?	297 +
		LA2	2	31	0.14	31	18.2	2	20.2
LASL - II	8*c	LA3	3	1930 rem*b	114 rem	2044 rem	1230	120	1350
		LA4	4	390	26.4	416	220	22	242
		LA6	6	186	10.7	196	120	12	142
		LA7	7	140	8.7	148	50	5	55
		LA8	8	55	4.37	59	33	3	36
		LA9	9	42	2.72	44	25	2.5?	27.5
		LA10	10	33	2.41	35	20	2	22
Argonne	4	A1	1	14.2 rep	145 rep	189 rem*d	14.2	145	159
		A2	2	9.6	116	146	9.6	116	126
		A3	3	5.5	55	71	5.5	55	60.5
		A4	4	0.8	10	12	0.8	10	10.8

*First column (R) designates code used in this report. Second column (L) designates patient code that appears in the literature.

*aRecalculation based on serum Na^{24} data.

*bThe rem values expressed in the LASL-I and II cases are based on an assumed RBE value of 5 for fast neutrons with an approximate depth dose penetration equivalent to that of 80 KV unfiltered X-rays.

*cData on patient LA5 not available.

*dBased on an assumed RBE value of 3 for fast neutrons.

Table II (continued)

Accident	Number Patients	Patient Code* R	Patient Code* L	Reported Total Body Dose Neutron	Reported Total Body Dose Gamma	Reported Total Body Dose Total	Calculated Total Body Dose Neutron	Calculated Total Body Dose Gamma	Calculated[*a] Total Rad Dose
USSR	2	R1	Kh	?	?	450	?	?	450[*e]
		R2	M	?	?	300	?	?	300
Oak Ridge	8	OR1	A	96 rad	269 rad	365 rad	96	269	365
		OR2	C	89	250	339	89	250	339
		OR3	D	86	241	327	86	241	327
		OR4	B	71	199	270	71	199	270
		OR5	E			236	62	174	236
		OR6	F	18	50.5	68.5	18	50.5	68.5
		OR7	G	18	50.5	68.5	18	50.5	68.5
		OR8	H	6	16.8	22.8	6	16.8	22.8
				Physical Estimate Total[*f]		Clinical Estimate Total			
Yugoslavia	6	Y1	V	840 rem		1000 – 1200 rem	320	320	640
		Y2	D	1024		700 – 1000	250	250	500[*g]
		Y3	M	856		700 – 1000	290	290	580
		Y4	G	920		700 – 1000	300	300	600
		Y5	H	696		600 – 800	210	210	420
		Y6	B	408		300 – 500	175	175	350
LASL - III	2	LA11	CWK			12000 rem[*h]	2300	6900	9200
		LA12	RSD			135			

[*e] Expressed in original report in r only with no mention of neutron or gamma components. Total rad doses are assumptions only.

[*f] Total rem dose. Neutron and gamma dose estimates not specified in original report.

[*g] Female patient whose weight is not available in the literature and might be considerably less than 70 KG standard man, the value used in calculating this dose. (See Table V, ORNL-2748, Part A.)

[*h] Estimate ± 50 per cent.

exposed to a mixed field of radiation in which the gamma-neutron dose ratio was about 10:1.

Patients 1, 2, and 3 were wearing film badges which were so blackened that it was necessary to evaluate the dose in terms of the reduced silver left after the development of the film. The gamma dose to Patient 4 was evaluated from a knowledge of his position and times of exposure to prompt and delayed fission gamma rays.

RUSSIAN ACCIDENT

At some undisclosed time, presumably prior to 1954, a reactor accident occurred in the U.S.S.R., resulting in the "short general external" exposure of two persons to neutrons and gamma rays. In the original report, doses of 300 r and 450 r were assigned to them but the gamma-neutron ratio in the radiation field was not reported. No information is available concerning the structure and composition of the reactor, and so it is not possible to estimate this ratio. In addition, the methods of dosimetry used are not described. The dose assignments must therefore be regarded as ambiguous.

OAK RIDGE ACCIDENT

A criticality accident occurred on June 16, 1958, in the Y-12 Plant at Oak Ridge, Tenn. Criticality was reached when an aqueous solution of an enriched uranium compound was drained inadvertently into a waste drum having dimensions such that a chain reaction resulted. Eight persons received general whole body doses from radiations emanating from the critical system: five of these received total doses in excess of 200 rad.

Film badges were not worn by any of those exposed to the radiation field. Blood sodium activity was chosen as the most reliable measure of neutron and gamma doses in this accident. The neutron dose to a man at a given distance from the assembly was deduced from the Na^{24} concentration in his body by employing a phantom (in this case a burro). The phantom was exposed to the neutron field escaping from a "mock-up" reactor of dimensions and composition similar to those of the accident assembly. This was accomplished within 24 hours after the accident. The blood serum Na^{24} level of the phantom resulting from irradiation by a measured neutron dose was determined and was used to convert blood activity data to neutron dose, assuming that the neutron spectrum did not vary with distance from the reactor. During another run of the same "mock-up" reactor, a measurement of the gamma-neutron dose ratio was made and was used to obtain the gamma doses. No deaths resulted from this exposure.

YUGOSLAVIA ACCIDENT

In an accidental supercritical excursion of a zero-power reactor on Oct. 15, 1958, at the Boris Kidrich Institute of Nuclear Sciences at Vinca, near Belgrade, Yugoslavia, eight individuals were irradiated. Six of them received significant doses of neutrons and gamma rays. One man died as a result of the irradiation.

Although only incomplete information was available concerning the neutron and gamma leadage spectrum from the reactor and the disposition of people and apparatus at the time of the accident, it was possible to make estimates of the doses from Na^{24} activation data for the six patients who were immediately flown to the Curie Foundation in Paris for treatment.

LOS ALAMOS ACCIDENT, LASL III

The most recent criticality radiation accident occurred on Dec. 30, 1958, at the Los Alamos Scientific Laboratory. In the course of a routine plutonium salvage operation, the material attained a critical state. A man who was standing in close proximity to the critical system received a lethal dose and died in 35 hours.

The dose to the middle of his body is thought to be distinctly higher than that to other portions of his body. The Na^{24} activity found in his body was used to obtain a whole-body average dose. The fast neutron dose was estimated to be 2,200 rad and the gamma ray dose to be 6,600 rad.

These dose estimates have recently been revised by Harris[1] and are summarized by him as follows:

Summary of Estimates of Radiation Exposure

Region and conditions	Fast neutron dose (rads)	Dose (rads)	Total dose (rads)
Head (incident)	2600	7800	10,400
Upper abdomen (incident)	3000	9000	12,000
Total body (average)	900	3000 - 4000	3900 - 4900

IV. THE CLINICAL MANIFESTATIONS OF THE ACUTE RADIATION SYNDROME

The clinical characteristics of the acute radiation syndrome in man have been learned from radiation accident cases, radiation therapy patients, and the casualties of atomic bombing. The outlines of a clear-cut symptom complex are confused by variations in types of radiation given, variations in the health of the recipients, and the feasibility of valid, controlled clinical observations. However, certain landmarks do emerge.

The general concensus is that when man is exposed to a single whole-body dose of ionizing radiation, he exhibits certain clinical signs, symptoms, and laboratory findings which are collectively termed the radiation syndrome. The frequency and severity of occurrence of these manifestations are roughly related to the dose received and the sensitivity of the individual patient. Exposures to less than 100 rad rarely result in clinical symptomatology; hence for our present purposes the radiation syndrome may be thought of as those clinical findings associated with total-body doses of radiation of over 100 rad.

The typical chronologic sequence of events following a large whole-body radiation exposure can be divided into four clinical stages:

the initial or prodromal stage
the latent stage
the manifest illness stage
the recovery stage.

The prodromal clinical findings include

anorexia
nausea
vomiting
extreme sweating
fatigue
prostration.

These changes remit in the latent period, which begins about two days later. After about two to three weeks of well-being a number of developments begin within a short time of one another. These symptoms of the manifest illness stage may include

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[1] Harris, P. S., Radiation Dose Estimation in the 1958 Los Alamos Criticality Accident, Health Physics, 5:37, 1961.

fever
overt or occult infections
scalp hyperesthesia and epilation
purpura and hemorrhage
diarrhea
ileus
cardiovascular collapse
severe lethargy
changes in sensorium.

By about the end of the sixth week after exposure the situation has usually been resolved and the clinical improvement of the surviving patients is rapid, although fatigue may continue for some time.

Dose-response relationships--About 15% of patients exposed to a dose of 100 rad may be expected to show some of the signs and symptoms of the syndrome. The frequency increases sharply up to the level of approximately 200 rad, at which level most of those exposed would be expected to exhibit some clinical symptomatology.

The occurrence of fatalities has been considered generally to begin at about 200 rad, increasing to 50% at about 450 to 500 rad. The findings of our survey of radiation accidents do not substantiate these estimates, probably as a result of therapeutic intervention. Death did not occur in any of these treated patients with known exposure to less than 500 rad. The LD_{50} is impossible to estimate on the basis of the small amount of such data accumulated thus far. However, it is reasonable to say that a fatal outcome is probably inevitable at about the 800 rad dose level.

V. RADIATION INJURY GROUPS

In spite of the implications in radiobiological literature, that there is a useful relationship between magnitude of exposure dose and severity of clinical sequelae, it is considered essential to approach the problem of individual patient management from a somewhat different standpoint. This is necessitated in part by the difficulty in obtaining quick and accurate dose estimates in accident situations which are usually very complicated. In addition, even if complete dosimetric information were available, the biological response of one individual to a known exposure would still differ from that of his confrere exposed under identical physical circumstances. We have, therefore, deemed it useful in the management of radiation accidents arbitrarily to divide patients showing various symptoms and signs of the acute radiation syndrome into five different "radiation injury" groups, as is shown in Table III.

Our five radiation injury groups are defined in terms of our present recognition and understanding of certain definitive clinical occurrences which have appeared in normal persons accidently exposed to external, penetrating, whole-body radiation overdosage. Briefly the pertinent characteristics of each group may be summarized as follows:

Group I: Most of these patients are asymptomatic; a few may have minimal prodromal symptoms.

Group II: These patients develop the acute radiation syndrome in a mild form. After transient prodromal nausea and vomiting, laboratory and mild clinical evidence of hematopoietic derangement dominates the picture.

Group III: A serious course occurs in these patients. Complications of hematologic malfunction are severe and, in the upper part of the group, some evidence of gastrointestinal damage may also be present.

Group IV: An accelerated version of the acute radiation syndrome occurs. Complications of gastrointestinal injury dominate the clinical picture. The severity of hematopoietic disturbances are related to the length of survival time following exposure.

Table III

Patients Classified by Clinical Radiation Injury Groups

Group	No. Patients	Patients by Code				
I	14	LA2	A1		OR6	
		LA6	A2		OR7	
		LA7	A3		OR8	
		LA8	A4			
		LA9				
		LA10				
		LA12*				
II	8	LA4		R2	OR1	Y6
					OR2	
					OR3	
					OR4	
					OR5	
III	6	LA1		R1*		Y2
						Y3
						Y4
						Y5
IV	2	LA3				Y1
V	1	LA11				
Total Patients -	31					

* Insufficient data for complete profiles; not included in averages.

Group V: A fulminating course with marked central nervous system impairment occurs in this group.

VI. ANALYSIS OF CLINICAL SIGNS AND SYMPTOMS

We shall now consider the clinical data in these cases.

The time of onset and of duration of clinical signs and symptoms in the prodromal or initial postirradiation period were analyzed. A similar compilation was made of the clinical phenomena of the stage of manifest radiation illness.

Great variations in the observations made, the clarity with which they were reported, the many forms of therapy employed, and the small number of cases involved make these data a somewhat imprecise basis from which to reach firm diagnostic and prognostic conclusions. Nevertheless, certain generalizations appear warranted.

INITIAL STAGE

The following Figure shows the frequency of several signs and systems, in the initial stage, after exposure to radiation.

The classic prodromal gastrointestinal symptoms of the acute radiation syndrome, i.e.

anorexia
nausea
vomiting

were present in all patients in Group III and above, within an hour after exposure. The time of onset and duration of these symptoms are not shown in the above Figure, but I shall mention the important ones. They generally continued for about two days. In Group II, the triad was somewhat slower in appearing, beginning within six hours, but continuing intermittently for about the same duration. Two of the eight patients did not vomit at all. Only 4 of the 14 Group I patients had anorexia or nausea, and only 2 of them vomited. In one of these, the symptoms occurred on the third day and were considered by the physician in charge as "a manifestation of anxiety and tension rather than radiation sickness."

The occurrence of diarrhea in this stage seemed to be of serious prognostic importance. Other than in the previously mentioned patient in Group I who had the anxiety reaction, this symptom occurred only in the Group IV and V cases, all three of which were fatal. It appeared on day 4 in both Group IV patients. In the Group V patient it started in 45 minutes, shortly after the onset of abdominal pain.

Weakness and fatigue were found in occasional Group I and II cases but were present and prolonged in all cases above that level of injury. Early prostration was also sometimes noted for a short time in Group II and above.

Other symptoms which were frequent almost exclusively in Group III and above included

conjunctivitis
erythema
sweating
paresthesias.

Oliguria in the initial stage was seen in only one Group IV case and the Group V case.

Immediate central nervous system symptomatology, including

ataxia
disorientation
cardiovascular collapse

were seen only in the latter patient. He later became comatose and died about 35 hours after radiation exposure with no evident latent period after the start of his illness. All other patients did have a variably long period of remission of early symptoms before the manifest illness stage began.

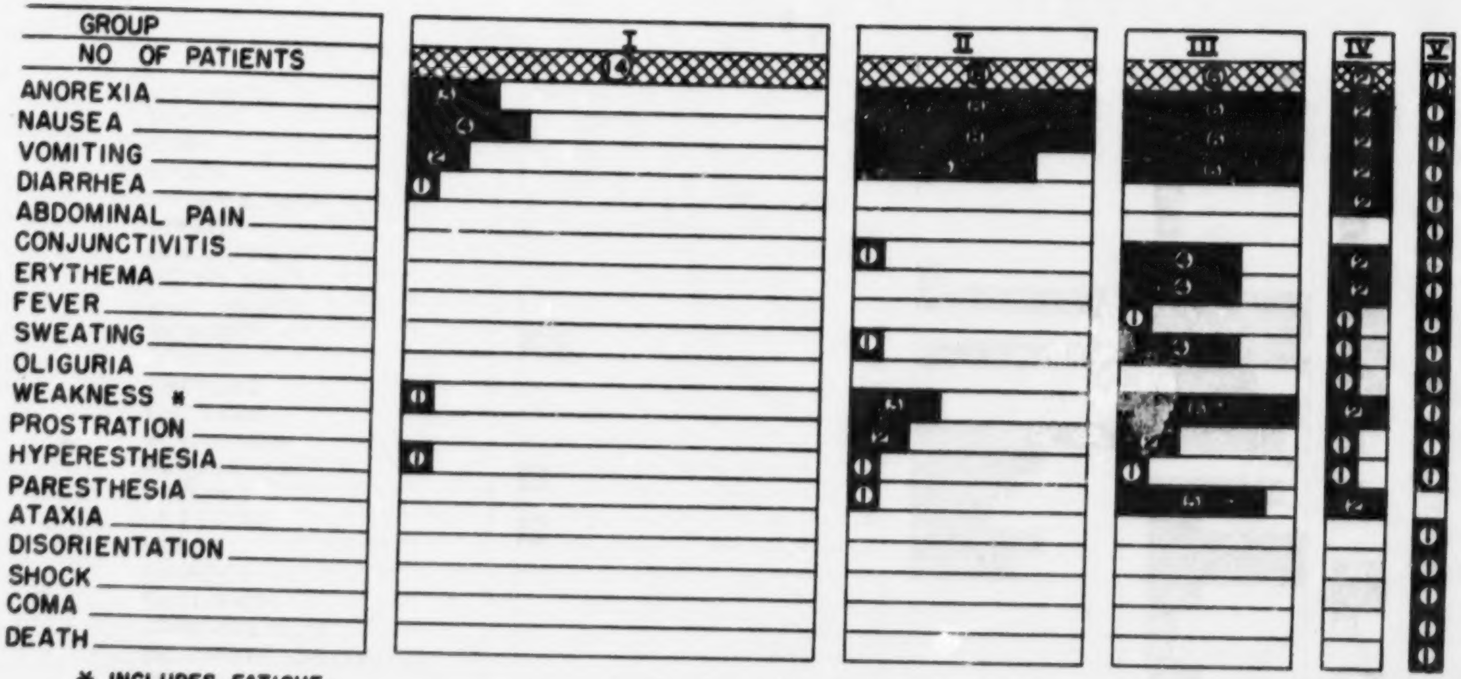
MANIFEST ILLNESS STAGE

The Figure below graphically represents the frequency of clinical signs and symptoms in the five "radiation injury" groups, that are manifest in the illness stage.

Patients in Group I showed no clinical evidence of illness of any kind after the initial stage subsided, except for one upper respiratory infection, one small retinal hemorrhage, and two complaints of weakness.

The most frequent finding above Group I was weakness and fatigue. This occurred in all cases. Onset in Group II was most often in the fifth or sixth week. In Group III and above it appeared almost immediately. Duration was variable, but generally the symptom lasted for several months.

Another common finding in all groups above the first one was epilation. Time of onset ranged from 13 to 20 days, with 10 of 14



* INCLUDES FATIGUE

FIG. 1

FREQUENCY OF CLINICAL SIGNS AND SYMPTOMS - INITIAL STAGE

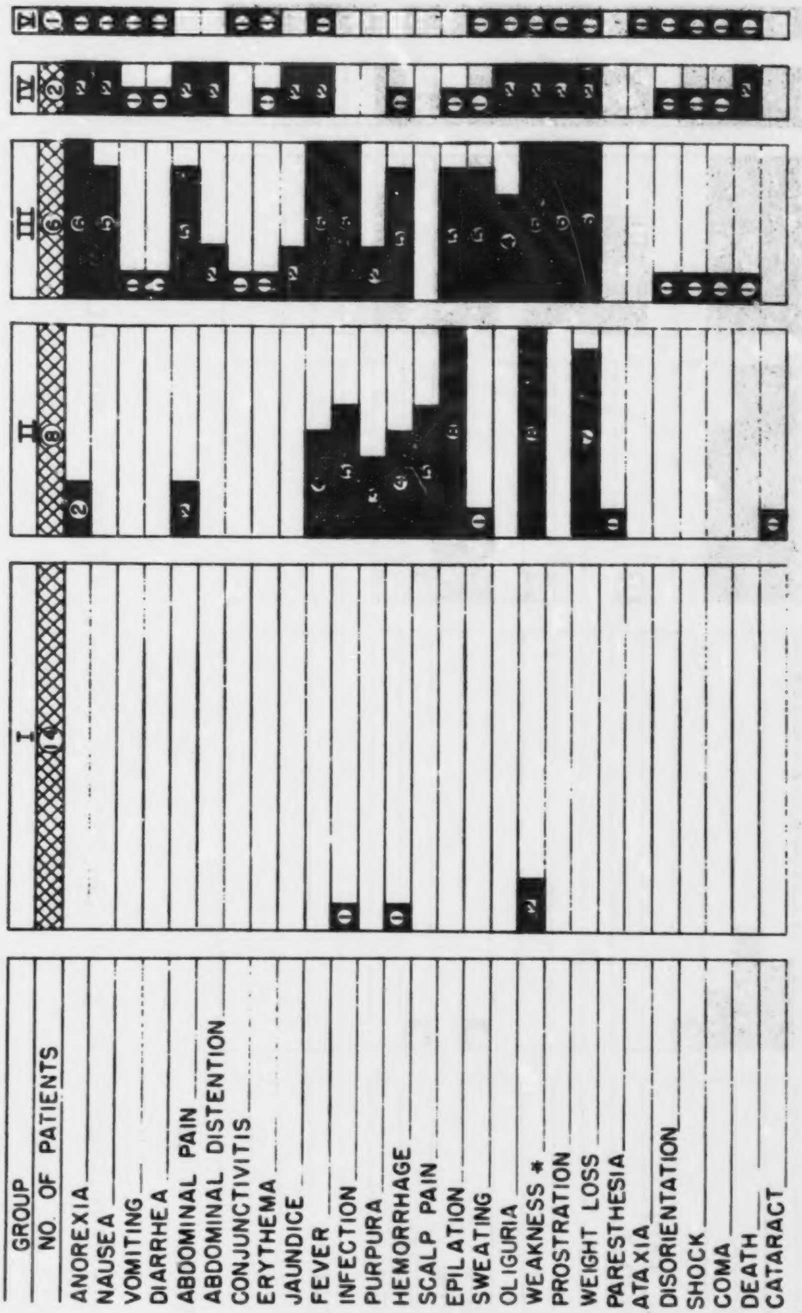


FIG. 2

FREQUENCY OF CLINICAL SIGNS AND SYMPTOMS
MANIFEST ILLNESS STAGE

patients beginning to lose hair between the 16th and 18th days. Two other patients, dying in one and one-half and in nine days, did not epilate. No data are given in the remaining case. No clear relationship of time of onset or of duration to injury group is evident.

Scalp hyperesthesia or pain occurred in most Group II patients one or two days before epilation. Similar findings were not noted in the higher groups.

Sporadic episodes of fever were observed in half of the patients in Group II and in all of these above that group. These were of short duration in Group II, but lasted one or more weeks in most of the more injured patients.

Clinical evidence of infection was seen between the second and fourth weeks in half of Group II, including two of the four febrile patients. In Group III all cases showed such indications. Definite clinical infection was not noted in Groups IV and V.

Hemorrhagic phenomena, such as

gingival bleeding
epistaxis
petechiae
purpura

were observed in most cases of Group II and above who survived beyond the third week. Serious hemorrhage was limited to two patients in the fourth postexposure week. One, in Group III, had menorrhagia and another in Group IV died with uncontrollable hematemeses and finally, hemoptyses.

In Group III and above a number of symptoms including

recurrent anorexia and nausea
abdominal discomfort
prostration
oliguria

appeared at the peak of manifest illness. These findings occurred earlier in the more acutely ill patients, who also had the additional symptoms of vomiting, diarrhea, and abdominal distention. Disorientation, shock, coma, and death followed in several instances.

Jaundice was noted in mild transient form at the end of this period in two individuals in Group III and in more marked form terminally in the two Group IV patients.

Weight loss was mild and not of long duration in Group II. In higher groups it appears to have been severer but details are somewhat scant.

Subsequent cataracts have been observed in one member of Group II. No other long-term effects have been reported.

VII. ANALYSIS OF LABORATORY DATA

A large number of laboratory examinations of many varieties were performed in the radiation accident patients discussed in this report. In order to consider and compare the laboratory observations, it was clearly necessary to develop a procedure for their analysis which would allow broad conclusions to be drawn despite differences in details of methodology employed in the diverse study centers.

The accepted normal range of results of each test procedure which was widely used among the cases under study, or which is recommended for such future use, was determined. A scoring system was then devised which assigned values from 1 to 4 of increasing deviation from the normal range. Using the resultant values, "profiles of injury" could be scored for the individual patients whose laboratory findings were so analyzed. These have been called "profile scores". The values assigned to the various deviations of laboratory tests from the normal range have therefore been designated "profile values", as shown in Table IV.

The profile values for hematological tests are given in this Table. Profile values were also assigned for coagulation tests and for biochemical tests of urine and of blood.

Table IV

Profile values assigned for various ranges of abnormaltiy
Hematology - peripheral counts

Test	Units	Normal*	Increase (above)				Decrease (below)			
			1	2	3	4	1	2	3	4
Hemoglobin	gms %	M-15.8 F-13.9	18 16	19 17	20 18	21 19	14 11.5	12 10	10 8.5	8 7
Erythrocytes	mill/mm^3	M- 5.4 F- 4.8	6.0 5.5	7.0 6.5	8.0 7.5	9.0 8.5	4.5 4.0	3.5 3.0	2.5 2.0	1.5 1.0
Hematocrit	vol. %	M-47 F-42	54 47	56 49	58 51	60 53	40 37	35 32	30 27	25 22
Leucocytes	1000/mm^3	7.4	12	18	24	30	4.0	3.0	2.0	1.0
Neutrophils	1000/mm^3	4.4	7.7	14	21	28.0	1.8	1.3	0.9	0.5
Lymphocytes	1000/mm^3	2.5	4.8	7.0	10	12.0	1.0	0.75	0.5	0.3
Platelets	1000/mm^3									
Rees-Ecker		405	545	700	850	1000	273	200	100	30
Brecher-Cronkite		257	440	600	750	900	140	100	50	30
Fonio		234	350	500	650	800	130	100	50	30
Dameshek		716	900	1000	1500	2000	500	350	100	30
Reticulocytes	% RBE	1.5	4	8	15	25	0.5	0		
Erythrocyte Sedimentation Rate	mm/hr	M- 5 F-10	10 20	20 30	30 40	40 50				

*Expressed as "universal mean" value - taken from Albritton [19]

Profile values were not assigned to tests which are not suited to this type of analysis.

Profile scores were determined for all possible tests in each individual case. These were analyzed individually and also cumulatively over the postexposure time period. Then, to facilitate intragroup comparisons, an attempt was made to determine the mean profile score for each radiation injury group on each type of test procedure at various convenient postexposure time intervals.

Unfortunately, it was found that only in the category of hematological tests were there a sufficient number of observations performed in uniform enough time periods in a large enough number of the accident patients to permit determination of mean profile scores for each clinical radiation injury group. It is possible, however, that profile scores for other tests might also be useful in the future, provided that they are performed at relatively frequent and consistent intervals.

We reviewed the hematological data with two main questions in mind. One is how much they aid in the assignment of an unknown case to a specific injury group. The other is how well they help to detect complications or therapeutic responses to the subsequent course.

Total blood count profile score is made up of scores for counts of erythrocytes or hematocrit, leucocytes, granulocytes, lymphocytes, and platelets. Other elements were omitted on the previously discussed grounds of infrequency and irregularity of tests. Figure 3 shows the group mean cumulative profile scores-hematology-total blood count.

When the means of such integral scores were cumulated by groups and graphed variation in the rate of accumulation of injury over time, and its maximum magnitude, were evidently closely related to the signs of clinical injury upon which injury group selection was based. It was possible to separate the mean score of cases falling into Group I and II from those of the sicker ones after 48 hours or less. Group V was also quite distinguishable from the outset. By the sixth day, Group I was distinct from II, and III from IV.

Examination of the ranges of the cumulative group mean scores portrayed in Figure 3 shows the value of blood count in indicating radiation injury. It also makes clear the difficulty of relying solely on this measure in the initial stage of radiation illness when there is considerable overlapping of group mean profile score ranges.

If one wishes to refine the estimation of injury group assignment further, certain individual tests which go into the previous total scores may be considered individually, as shown graphically in Fig. 4.

The lymphocyte scores appeared to be the best prompt laboratory indicators of radiation injury. In 48 hours Groups II, III, IV, and V were well separated in mean score. However, a few of the Group II cases showed little early lymphocyte fall and the opposite occurred in Group I, so that there remained some overlapping of the two lower groups. This is shown in Fig. 5.

The neutrophil score did not facilitate differentiation of Groups I and II. Nevertheless, it was useful supportive evidence in separating the two lower groups from the three higher ones by Day 3. Also groups III and IV were becoming distinct on Day 3 by this means. However, Group I and II were not separable for the first month, as shown in Fig. 6.

The leukocyte score gave rather similar information but not as distinctly as did the neutrophil score. This was, of course, a reflection of the fact that neutrophil variations account for most of the white count changes, but lymphocyte shifts are also involved. Thus the distinction between Groups I and II, as shown in Fig. 7, was present earlier here than in the neutrophil score.

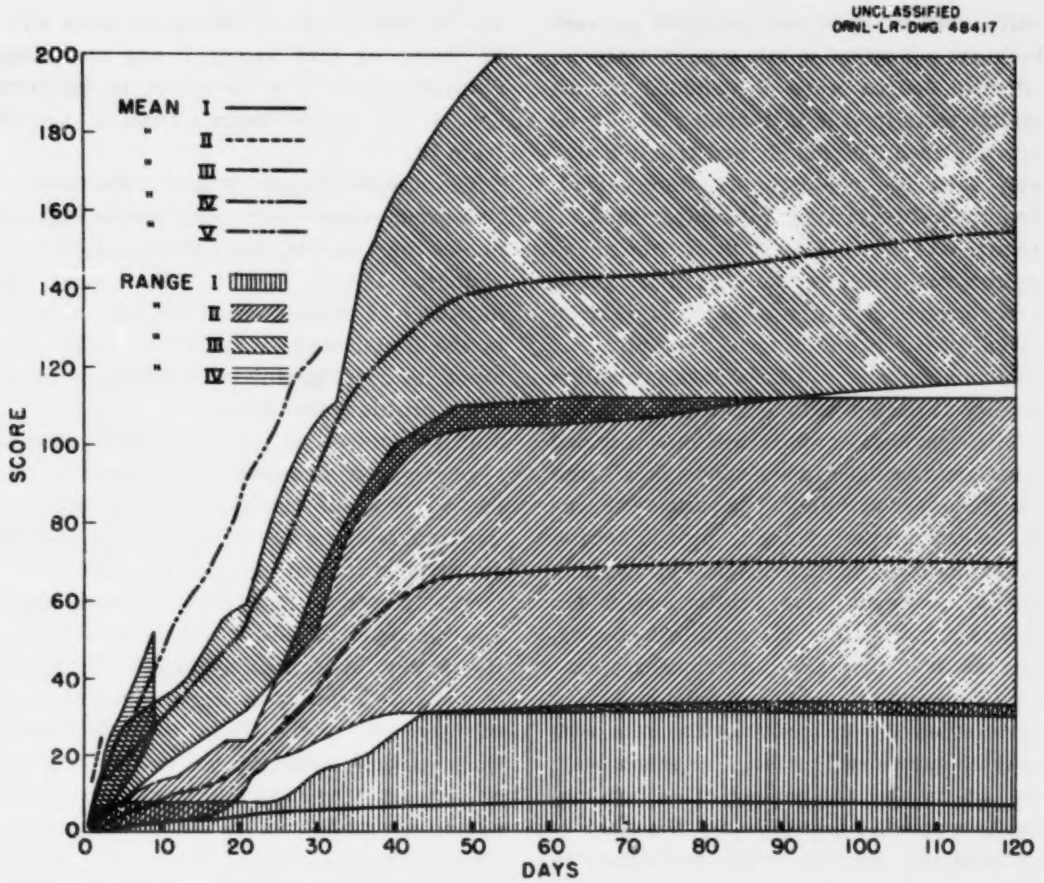


FIG. 3
GROUP MEAN CUMULATIVE PROFILE SCORES-
HEMATOLOGY-TOTAL BLOOD COUNT

The platelet score was not very useful in the early days after exposure. However, the differentiation of Group IV from Group III was apparent by this test as early as Day 6. After the third week, sharp changes separated Groups II and III from the unaltered Group I, as can be seen in Fig. 8.

Erythrocyte scoring was least helpful early. There was a reversal of Groups III and IV. However, a difference between Groups II and III was discernable after the first month. Therapeutic efforts, such as transfusion and some pre-exposure abnormalities confused the data from this test.

BONE MARROW

In general, relation of appearance of an aspirated sample of marrow to amount of injury or prognosis is not sufficiently obvious to use in making injury group assignments. There is a hypocellularity from the early period after exposure, with depression of the granulycytic series in particular. Mononuclear cells of the reticulum and plasma cell varieties remain, with variable concentrations of erythroid precursors. Megakaryocytic diminution and deterioration is present later. Regeneration of erythroid and myeloid

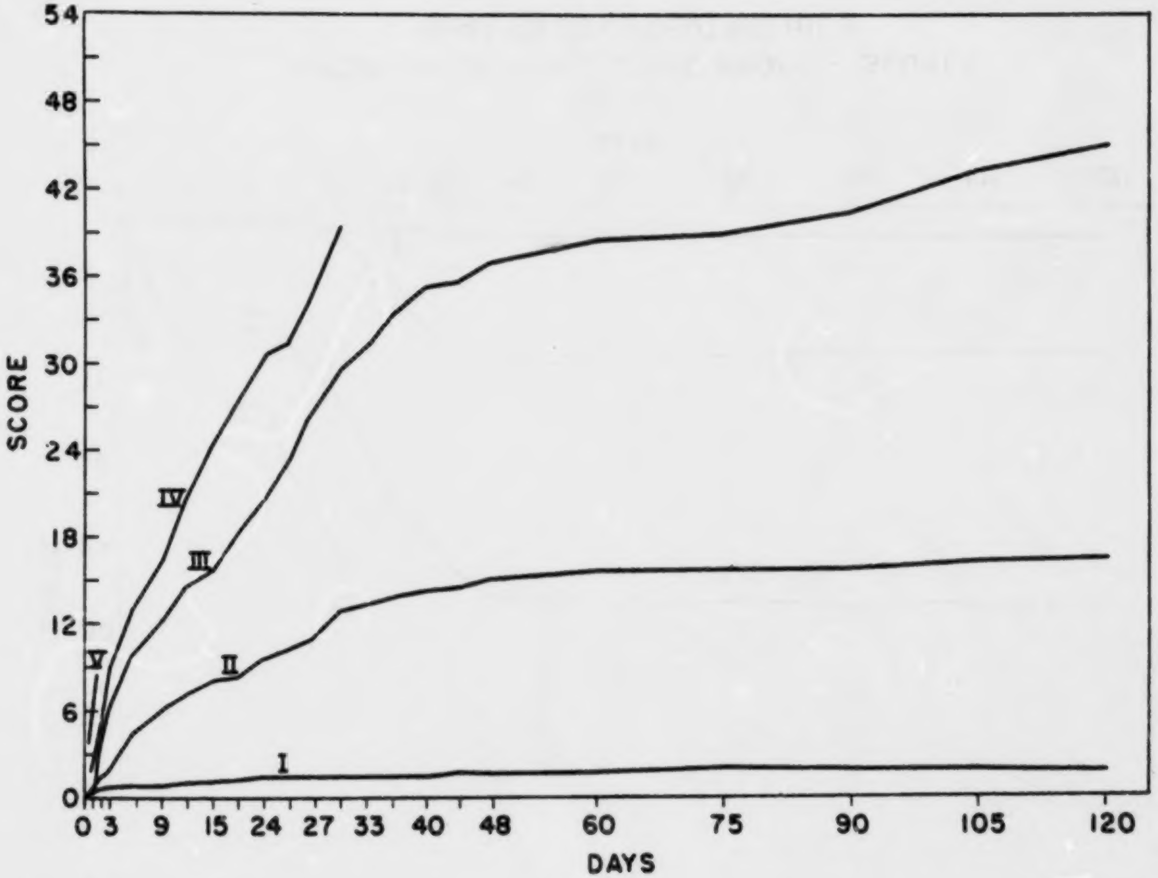


FIG. 4

GROUP MEAN CUMULATIVE PROFILE SCORES
HEMATOLOGY - LYMPHOCYTES

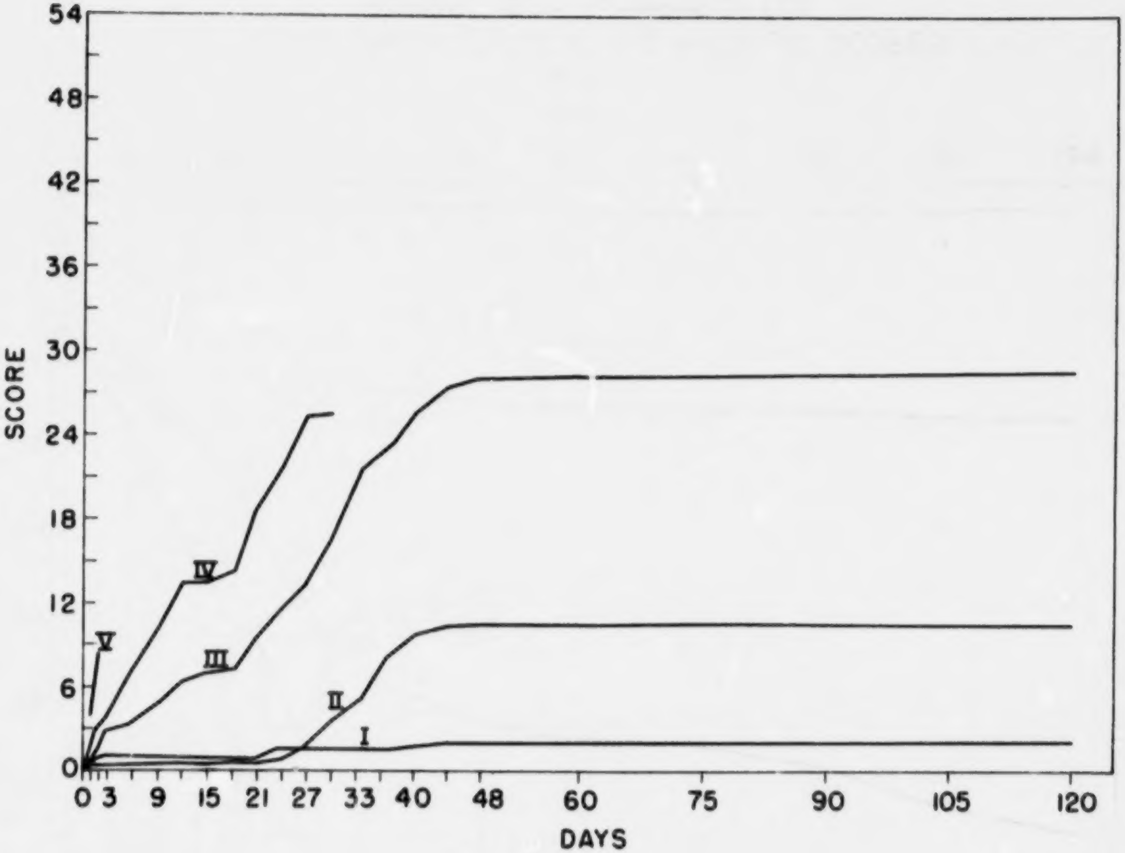


FIG. 5
GROUP MEAN CUMULATIVE PROFILE SCORES
HEMATOLOGY -NEUTROFHILS

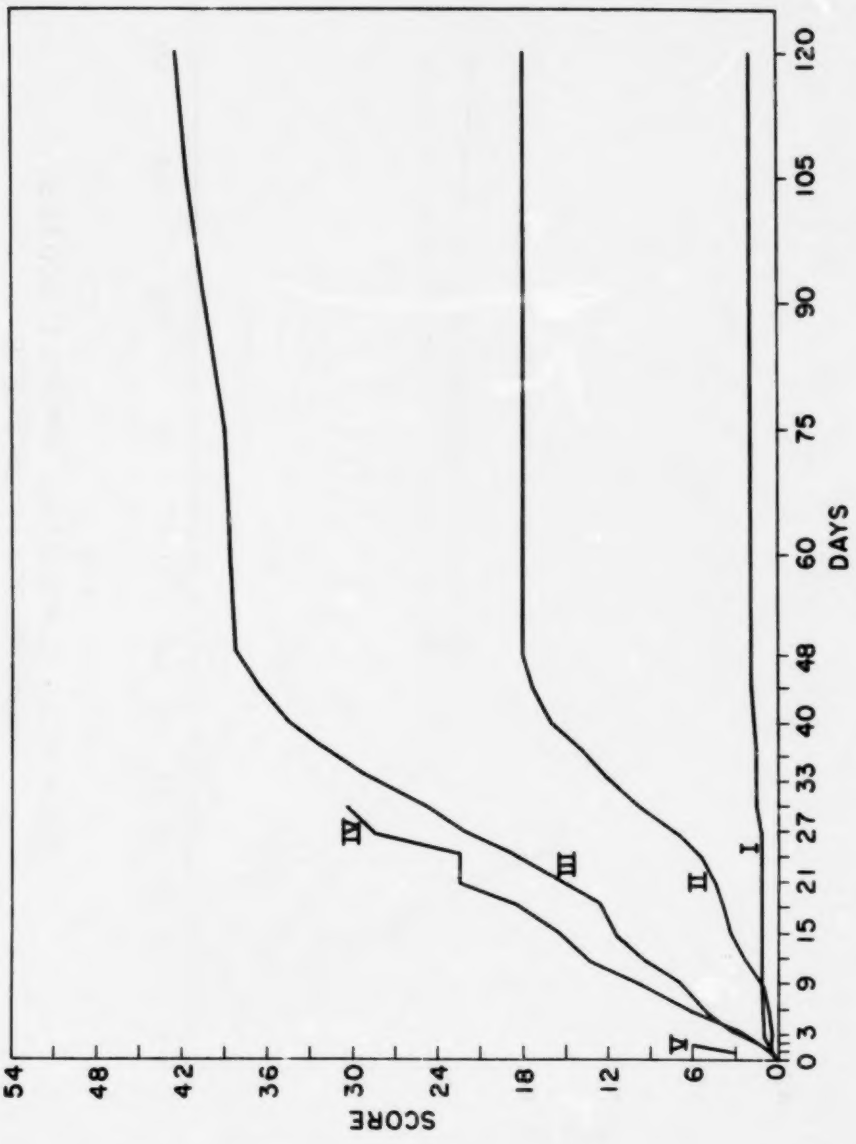


FIG. 6

GROUP MEAN CUMULATIVE PROFILE SCORES
HEMATOLOGY - LEUCOCYTES

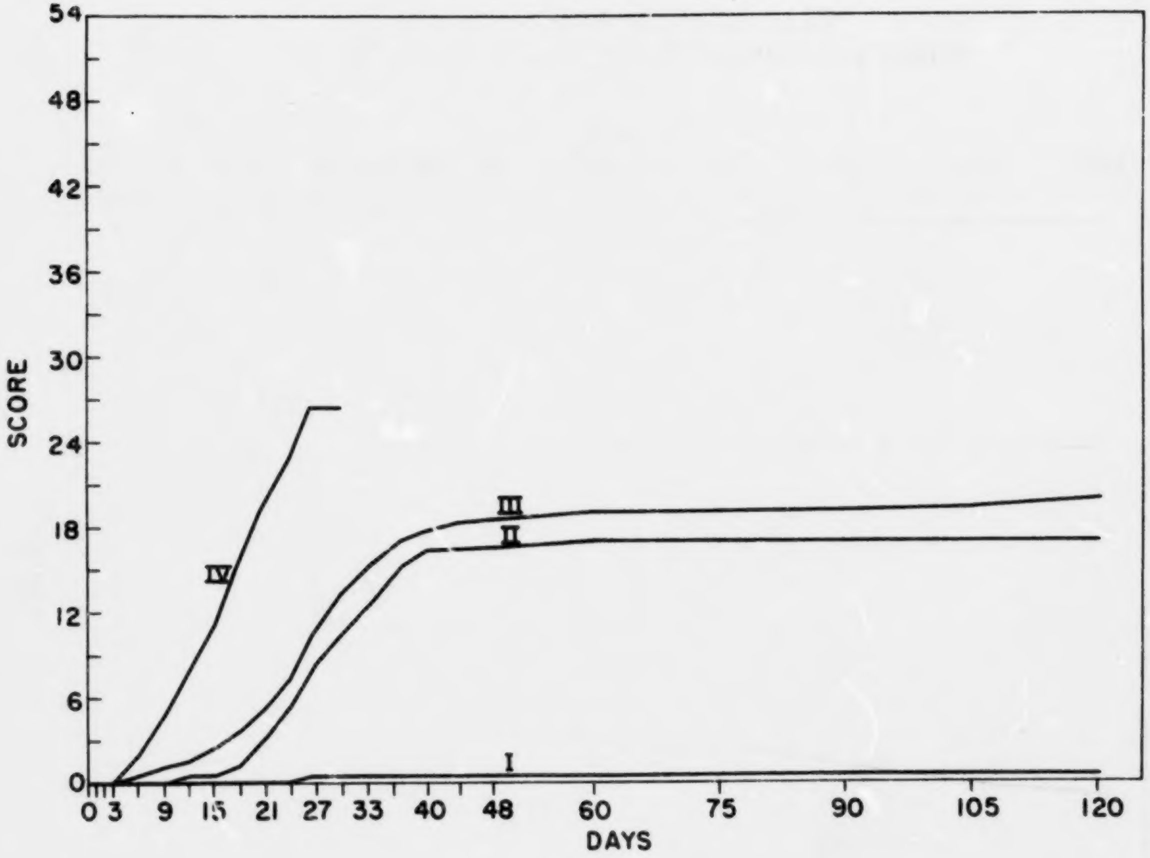


FIG. 7
GROUP MEAN CUMULATIVE PROFILE SCORES
HEMATOLOGY - PLATELETS

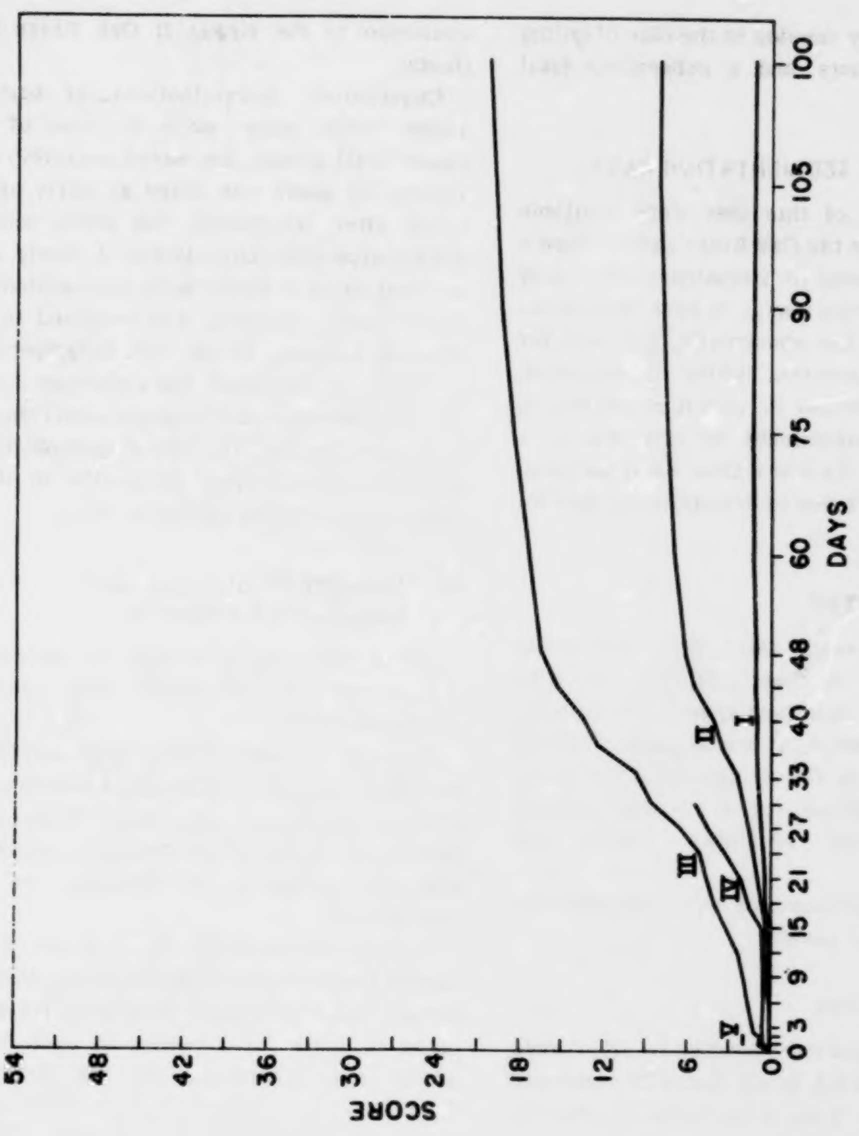


FIG. 8

GROUP MEAN CUMULATIVE PROFILE SCORES
HEMATOLOGY-ERYTHROCYTES

precursors may develop in the face of falling peripheral counts and a subsequent fatal outcome.

ERYTHROCYTE SEDIMENTATION RATE

The results of this test were available serially only in the Oak Ridge cases. Here a close relationship of elevation to the early stages of infection seems to have been present. However, the abnormality persists far beyond the infection which it heralded. Further data would be useful in evaluating the apparent usefulness of this test as a warning of infection at a time when the usual signs, such as fever or leucocytosis, may not be of service.

BLOOD CHEMISTRY

Many biochemical tests were carried out on the blood of these patients, but none revealed any alterations specific to radiation injury. There were, of course, abnormalities associated with the symptomatology of the radiation syndrome, e.g. electrolyte changes associated with prolonged nausea and vomiting.

There was evidence of hyperbilirubinemia in 3 of the fatal cases.

URINE CHEMISTRY

Urinary output was recorded for all patients except R1 and R2. In all Group III cases and above, except LA1, a decrease to oliguric levels was noted during the critical period of the manifest illness stage.

There were no significant effects in either total nitrogen, amino nitrogen, or uric acid excretion in the Group II Oak Ridge Patients.

Quantitative determinations of urinary amino acids were made in most of the cases in all groups. Increased excretion of a variety of these was noted as early as 12 hours after irradiation, but there was no quantitative dose correlation. A newly discovered urinary amino acid, beta-aminoisobutyric acid (BAIBA), was excreted in increased amounts by the Oak Ridge patients in Group II. Excretion was maximum during the first few days after exposure and returned to normal by Day 10. The magnitude of the increase in excretion of BAIBA in these cases appears to be related to dose.

VIII. SUMMARY OF CLINICAL AND LABORATORY FINDINGS

Out of this maze of clinical and laboratory data a total picture of the acute radiation syndrome evolves.

The next two figures taken from Gerstner's excellent review[1] graphically illustrate the clinical course of the Hematologic form (Group II) of the acute radiation syndrome and the temporal relationships of this course.

In order to establish basic points of reference for the hematologic laboratory findings in the acute radiation syndrome the blood count findings for a patient in each injury group are presented in the following figures.

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[1] Gerstner, H. B., Acute Clinical Effects of Penetration Nuclear Radiation, J. Am. Med. Assoc., 168:381, 1958.

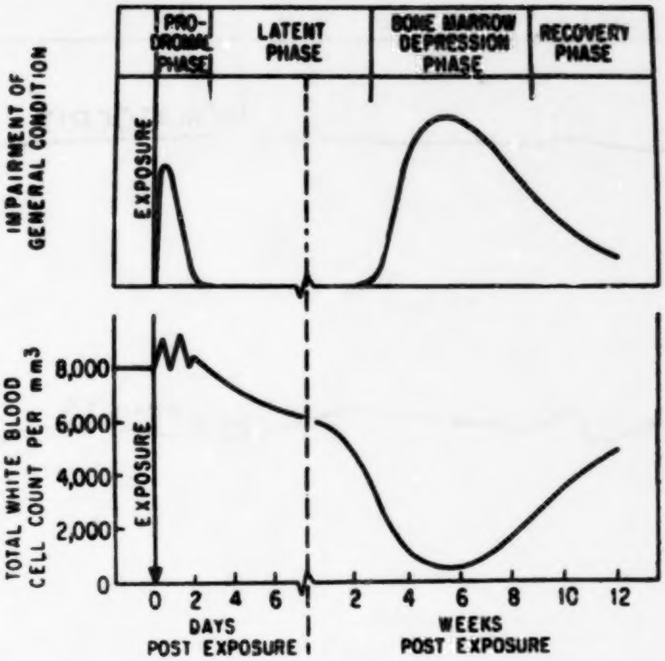
PRO-DROMAL PHASE
LATENT PHASE
BONE MARROW DEPRESSION PHASE
RECOVERY PHASE
IMPAIRMENT OF GENERAL CONDITION
EXPOSURE
TOTAL WHITE BLOOD CELL COUNT PER mm3
8,000
6,000
4,000
2,000
0
EXPOSURE
0
2
4
6
1
2
4
6
8
10
12
DAYS POST EXPOSURE
WEEKS POST EXPOSURE

Fig. 9

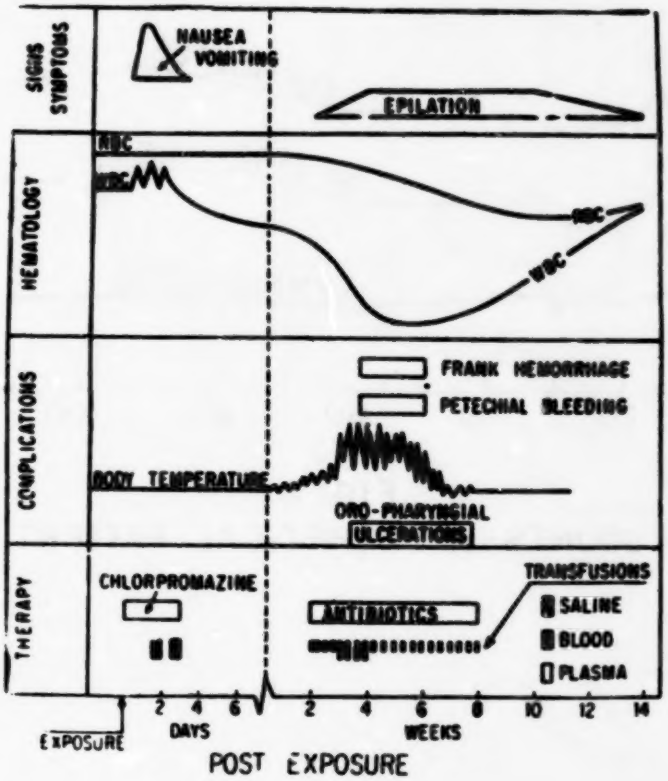
SIGNS SYMPTOMS
NAUSEA
VOMITING
EPILATION
HEMATOLOGY
RBC
WBC
RBC
WBC
COMPLICATIONS
FRANK HEMORRHAGE
PETECHIAL BLEEDING
BODY TEMPERATURE
ORO-PHARYNGIAL ULCERATIONS
THERAPY
CHLORPROMAZINE
ANTIBIOTICS
TRANSFUSIONS
SALINE
BLOOD
PLASMA
EXPOSURE
2
4
6
2
4
6
8
10
12
14
DAYS
WEEKS
POST EXPOSURE

Fig. 10

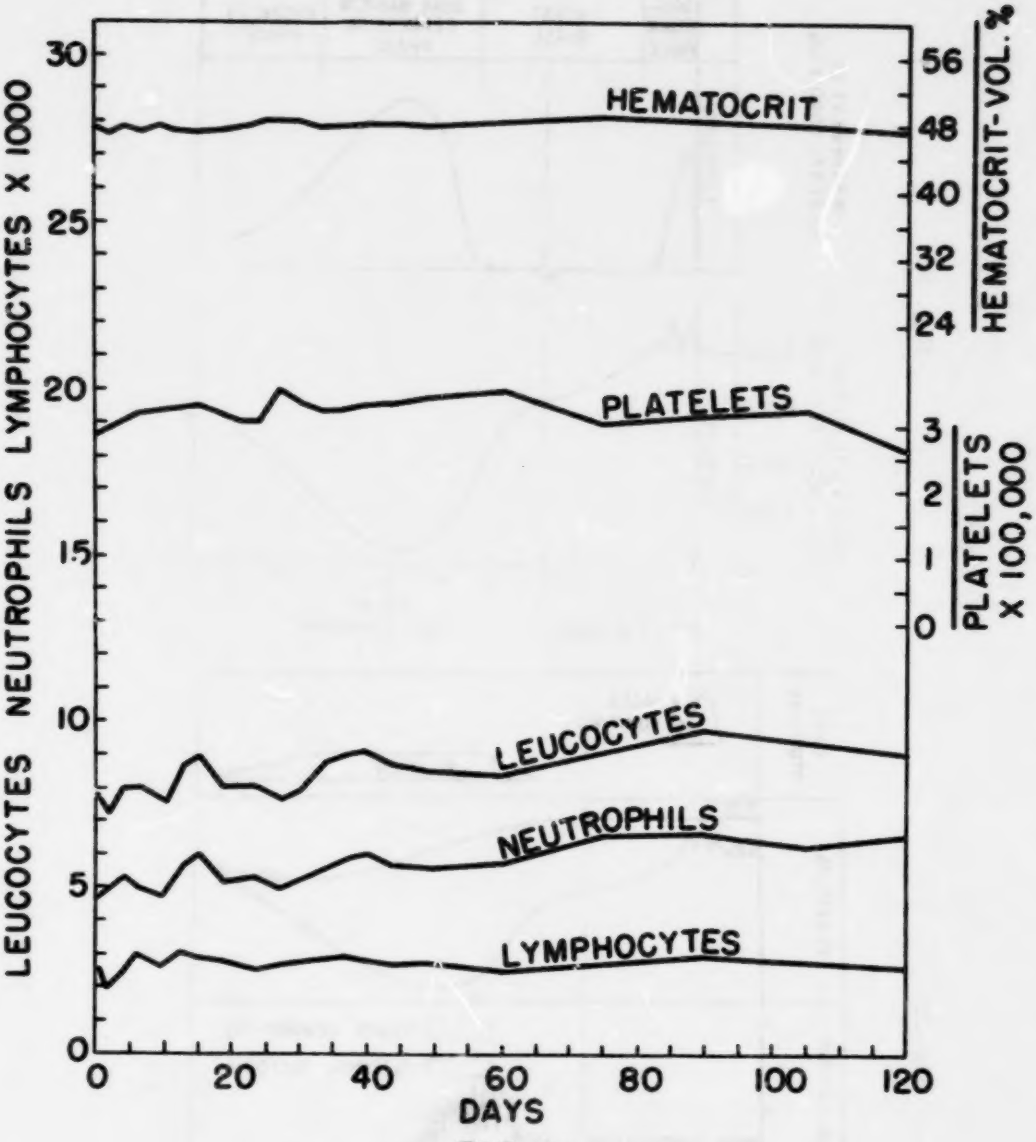

FIG. 11

BLOOD COUNTS-HYPOTHETICAL PATIENT 1

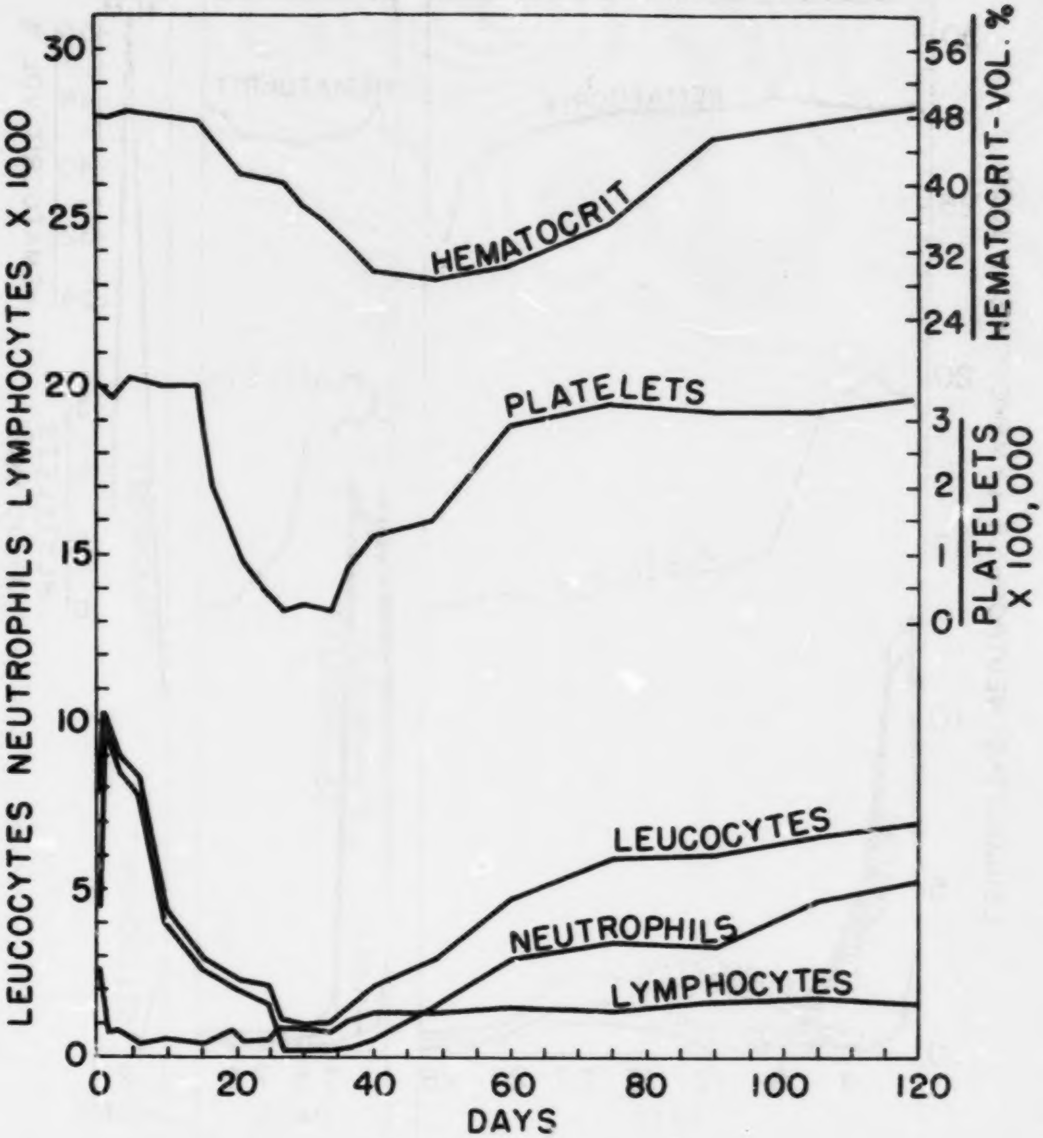

FIG. 12
BLOOD COUNTS-HYPOTHETICAL PATIENT 2

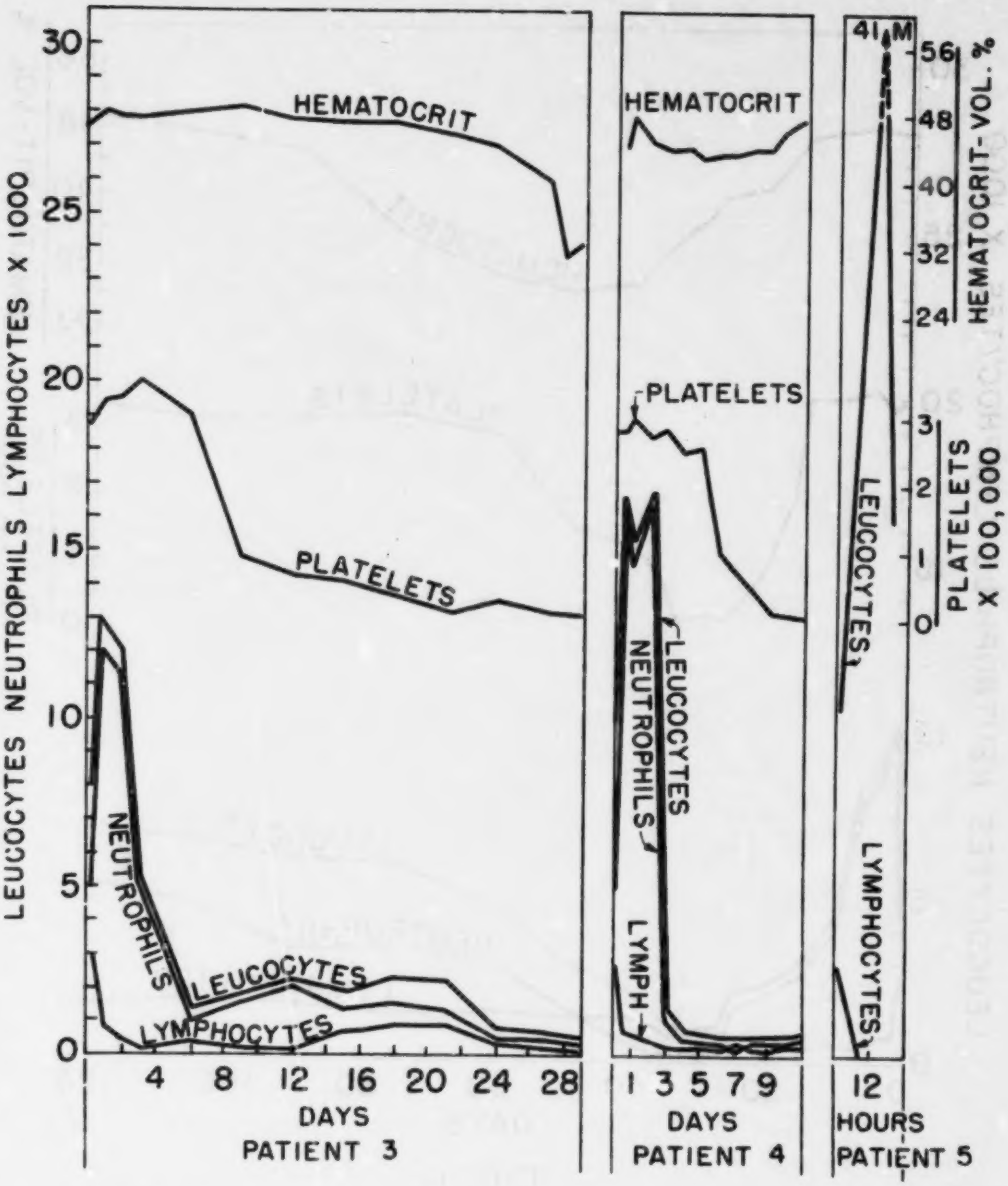

FIG. 13
BLOOD COUNTS
HYPOTHETICAL PATIENTS 3, 4, AND 5

Management of the Acute Radiation Syndrome

I. INTRODUCTION

The selection and time of performance of appropriate diagnostic and clinical procedures will be strongly influenced by three kinds of knowledge.

1) The clinical acumen and judgment which would be brought to bear on the medical management of any patient.

2) An awareness of the underlying pathophysiology of the acute radiation syndrome in man.

3) A general idea of the magnitude and type of radiation to which the patient has been exposed.

Discussion of the first of these is beyond the scope of this duscussion. The next two have already been mentioned, but their application in the individual accidental exposure case warrants some further consideration.

In a given accident, the exposure dose would seem to be the logical piece of information which upon clinical management can be planned. As has already been indicated, however, it is not necessarily helpful in the individual case for two reasons:

1) First, the dose, if it can be determined, is usually not available as soon as needed.

2) Second, no given individual will necessarily respond exactly as his confreres in a given dose category.

Therefore, the highest priority diagnostic recommendations in the early postexposure period are planned for the accumulation of sufficient information to establish the response "profile" of the individual under study in comparison with those of others who were studied in a similar manner after whatever dose of radiation. When this information is available, a reasonably accurate prognosis can be made and planning of clinical management can proceed even in the absence of dosimetry information. It is highly desirable, of course, to obtain physical dosimetry data as soon as possible to supplement the clinical estimate of injury.

Subsequent tests will be recommended to serve four purposes:

1) to validate the original diagnostic and prognostic conclusions in the patient

2) to detect promptly the development of clinical complications in the patient's course

3) to provide more data for improved profile scoring of future cases

4) to supply more information about radiation pathophysiology.

II. DIAGNOSTIC PROCEDURES

Given one or more individuals who have accidentally received, in all probability, a significant acute injurious radiation overexposure of neutron and/or gamma ray type, how would the attending physician proceed? It is rather obvious that in our present state of knowledge of human radiation injury there really is no procedure which might not be productive of some new information of immediate or eventual applicability. However, it is also obvious that diagnostic tests must include those that are most essential and none that are detrimental to the individuals involved. The resultant limitation in number and frequency makes a well-informed selection all the more important.

In the course of this analysis of all available criticality accidents, certain diagnostic hints have emerged which may aid in dealing with similar situations in the future. These procedures are listed in Table V.

Table V. Recommended diagnostic procedured for clinical management of radiation injury

Group	I-II-III-IV			I	II			III		IV	V
Time (d)	1	2	3	STT	STT	18–48	STT	4–48	STT	4	1
Type A Procedures											
History											
Symptoms) onset	x	x	x	x	x	D	x	D	x	D	D
Signs) duration	x	x	x	x	x	D	x	D	x	D	D
Past Medical	x										
Physical Examination											
General						d 21	3 mo$^+$	d 15–30	6 mo$^+$	d6	D
Body weight	x			x	x	D	x	D	x	D	D
Urinary output	x	x	x		x	D		D		D	6hr
Laboratory Tests											
Hematology											
Hematocrit	x	x	x	x	x	D	x	STT	x	D	6hr
Leucocytes	x	x	x	x	x	D	x	D	x	D	6hr
Differential Count	x	x	x	x	x	D	x	D	x	D	6hr
Calculation of Total Neut. and Lymph	x	x	x	x	x	D	x	D	x	D	6hr
Platelets	x	x	x	x	x	D	x	STT	x	D	6hr
Bone Marrow Aspiration				d 30	14d	14d	mo6	14d	mo6	7d	d1
Radioassay											
Blood Na^{24}	x	x									
Whole Body Counting	x	x									
Type B Procedures											
Laboratory Tests											
Hematology											
Sedimentation Rate	x	x	x	x	x	D	x	D	x	D	6hr
Reticulocytes	x	x	x	x	x	D	x	STT	x	D	6hr
Bleeding) Clotting) Times	x					STT		STT	–75d	3d	6hr
Biochemistry											
Blood											
NPN	x	prn	prn					prn		STT	6hr
Sodium	x	prn	prn					prn		prn	d1
Chloride	x	prn	prn					prn		prn	d1
Potassium	x	prn	prn					prn		prn	d1
pH or CO_2	x	prn	prn					prn		prn	d1
Urine											
Routine analysis	x	x	x		x	D	x	D	x	D	6hr
Stool											
Occult blood	x					D		d 12$^+$		D	All
Opthalmology											
Slit lamp			x	6 mo$^+$			6 mo$^+$		6 mo$^+$		
Type C Procedures											
Biochemistry											
Serum bilirubin	x	x	x		x	STT		STT	–30d	D	6hr
Urine BAIBA	x			–30d	x	D		D		D	D

RECOMMENDED FREQUENCY OF TIME OF PERFORMANCE

STT – Standard Testing Times: 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36, 40, 44, 48, 60, 90, 105, 120 days; 6 months, 1 year, and annually.
x – at times indicated in column heading.
d – day(s).
D – daily during time indicated in column heading.
nD – frequency in days.
–Dn – up to and including day at times indicated in column heading.
Dn$^+$ – on and after day at times indicated in column heading.
Dn – specific day recommended.
n – all time after day specified.
prn as indicated by clinical course.

Further experience may alter these recommendations completely, but at this time the procedures listed in this Table seem to be the most likely to facilitate preliminary clinical evaluation and subsequent management.

Frequency and duration of test performances are given. Suggestions based on the analysis of previous studies are made for each of the five clinical injury groups. In line with the objectives of these diagnostic recommendations, test procedures have been categorized as Type A, B, or C, as shown in the above Table.

Type A procedures are of particular applicability in the early diagnostic and prognostic appraisal of clinical radiation injury.

Type B procedures are of more help in confirming the earlier estimations of injury and in recognizing and managing the development of complications.

Type C procedures are of possible but not yet verified value for future use in either of the two previous categories. In order to determine their suitability, they should be utilized when feasible.

While this procedural outline is thus segmented, somewhat arbitrarily, for the sake of clarity of presentation, it should be clearly understood that each individual case must be viewed and studied in its own right as the particular symptomatology and course require. It should also be recognized that it is beyond the purpose of this listing to include specific recommendations for future scientific lines of investigation of the acute radiation syndrome. Such radiobiological studies, while assuredly desirable, must emanate from the interest and availability of appropriate research personnel in each particular instance. For the purposes which have stimulated the preparation of this report it should suffice to point out that the accumulation of good basic clinical and laboratory data in a consistent and logical form from these unfortunate episodes will itself be a distinct contribution to radiobiological knowledge as well as a means of facilitating clinical patient management.

III. PRELIMINARY EVALUATION OF RADIATION INJURY

An attempt has been made, utilizing the early clinical data recorded in the past accident cases, to identify those findings which have the greatest early prognostic value by indicating the correct injury group assignment and thus subsequent clinical course. On this basis a plan has been drawn up which should aid in planning for subsequent patient care. It is briefly summarized in the following Figure.

This evaluation plan rests on the early and accurate performance of two familiar diagnostic procedures

continuous detailed clinical observations
blood counts.

The necessary clinical observations include a complete history of the immediate episode as well as of previous and preexisting abnormalities in health. A complete physical examination is indicated both to find any abnormalities present and to serve as a base-line observation for subsequent changes. Items of particular interest are the exact time of onset and duration of symptoms and signs. Central nervous system and gastrointestinal findings are of greatest importance in the preliminary evaluation process.

The blood counts should include

erythrocyte count and/or hematocrit
leukocyte count
differential count
calculated total lymphocytes and neutrophils
platelet count.

They should be performed at least once daily for the first three days. To evaluate the results, the blood count profile scoring method is recommended.

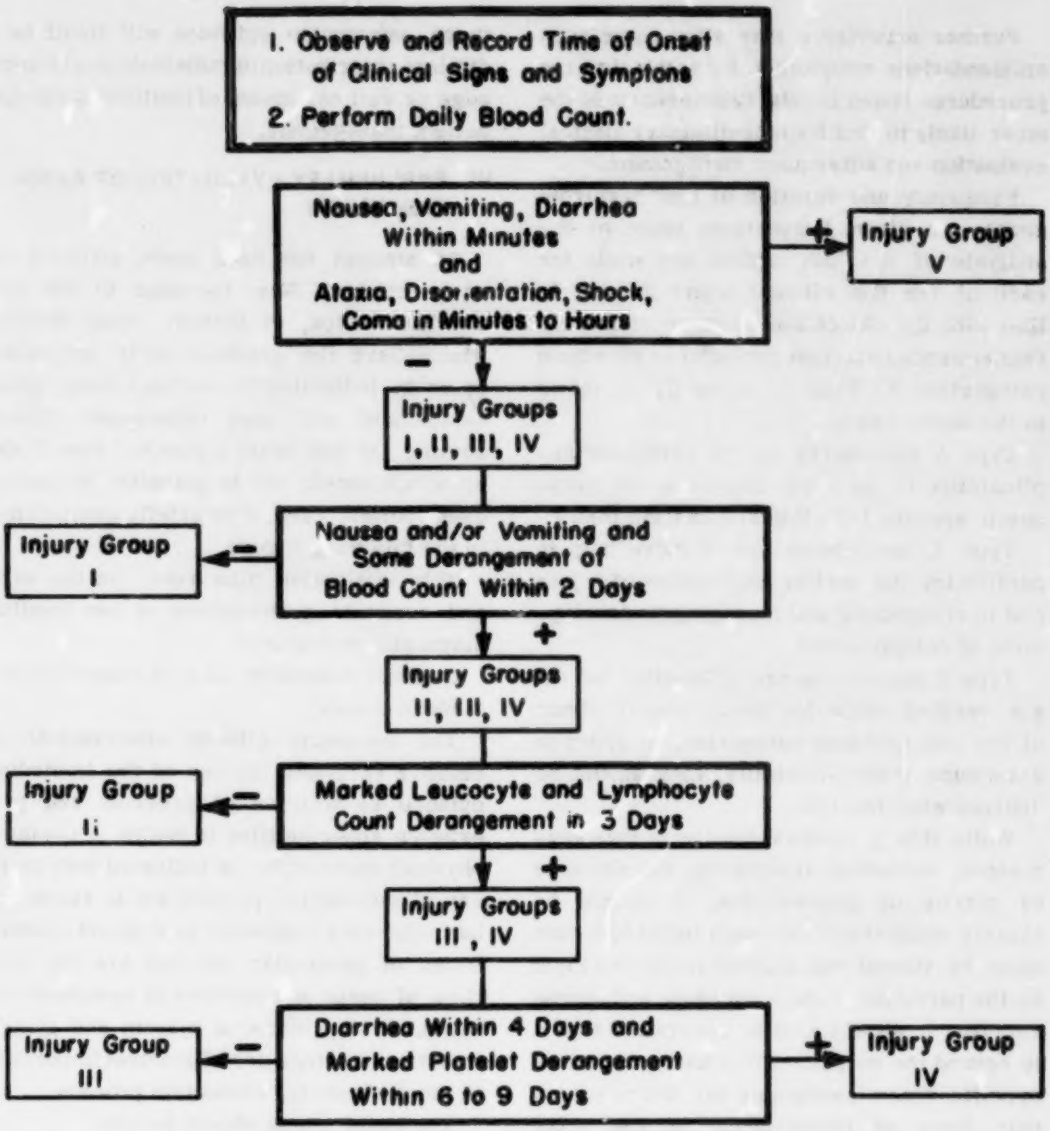
1. Observe and Record Time of Onset of Clinical Signs and Symptons
2. Perform Daily Blood Count.
Nausea, Vomiting, Diarrhea Within Minutes and Ataxia, Disorientation, Shock, Coma in Minutes to Hours
+
Injury Group V
−
Injury Groups I, II, III, IV
Nausea and/or Vomiting and Some Derangement of Blood Count Within 2 Days
−
Injury Group I
+
Injury Groups II, III, IV
Marked Leucocyte and Lymphocyte Count Derangement in 3 Days
−
Injury Group II
+
Injury Groups III, IV
Diarrhea Within 4 Days and Marked Platelet Derangement Within 6 to 9 Days
−
Injury Group III
+
Injury Group IV

FIG. 14

PRELIMINARY EVALUATION OF RADIATION INJURY

IV. CLINICAL MANAGEMENT

As in the case of diagnostic procedures, a consideration of the choice and results of past methods of therapy helps to shape the present recommendations.

The types of agents employed in the accidents reported herein are listed in Table VI. It will be seen that only in cases which fall into Group II or above has treatment appeared necessary. In general, since the means to reverse the basic cellular mechanisms which underlie radiation effects are not yet at hand, specific therapy is reserved for symptomatic indications.

It is desirable for all cases with a probability of significant acute injurious radiation overexposure to be hospitalized for close observation. The accomplishment of the preliminary estimation of clinical radiation injury as described in the preceding section on diagnostic procedures should indicate within 72 hours those cases falling into Group II or above. These should be kept hospitalized.

The others can be reassured of their favorable prognosis and released from inpatient care when asymptomatic.

GROUP I - These patients can be followed as outpatients, using the previously suggested tests. There is no specific medical contraindication to a return to work as soon as dosimetry, clinical symptoms and findings, and laboratory data have established the low level of overexposure. Considerations of public opinion, medicolegal sequelae, and the like, doubtless have played a role in the more conservative prescription of a rest period of varying length which has been utilized in several cases within Group I. It is definitely recommended that subsequent work be in a capacity in which further radiation overexposure is unlikely.

GROUP II - Patients in this group will exhibit transient nausea and vomiting which will probably not require more than the administration of antiemetic agents, if that. There is no definitive therapeutic procedure for radiation epilation other than reassurance concerning its impermanence.

Complications of the existing bone marrow damage, such as anemia, infection, and evidences of bleeding, have been mild when present at all in Group II. It is therefore considered advisable to adopt a conservative attitude of watchful waiting, with the means for vigorous and definitive treatment available if and when needed. Thus, blood and perhaps platelet transfusions, antibiotics, and the like should be ready in reserve. An attempt to reduce the likelihood of infections by emphasis on personal hygiene and the use of aseptic isolation methods may well be warranted.

The mechanism of the observed weakness and fatigue of these patients is not clear, and therefore no specific therapy can be recommended at this time. Rest is indicated until symptoms and major laboratory abnormalities subside. The opportunity for future occupational radiation exposure should be minimal.

GROUP III - It is the therapeutic management of patients in Group III that presents the most challenging opportunity to alter an otherwise unfavorable prognosis. In this group one can expect to deal with the major complications of serious bone marrow damage, some gastrointestinal injury, and secondary renal and cardiovascular problems.

Prompt bed rest, bland diet, good nursing care, and a realistic but generally reassuring appraisal of the medical situation are indicated as soon as dosimetry, symptomatology and hematological "profile" makes classification in Group III apparent.

Antiemetics are indicated for severe and prolonged nausea and vomiting in the initial phase or later. Intravenous feeding may be necessary as well, to maintain fluid and caloric balance in the early stage or in the

Table VI

Summary of therapeutics employed in radiation accident cases

Therapy	Group II								Group III						Group IV		Group V
	LA4	R1	R2	OR1	OR2	OR3	OR4	OR5	Y6	LA1	Y2	Y3	Y4	Y5	LA3	Y1	LA11
Sedation						X											X
Analgesics		X				X				X					X		X
Antiemetics				X		X	X	X									
Antispasmodics		X				X											
Parenteral fluids	X									X					X		X
Whole Blood	X	X	X						X	X	X	X	X	X	X	X	
Plasma	X														X		X
Platelets											X	X				X	
Bone marrow											X	X	X	X		X	
Antibiotics	X	X	X	X			X		X	X	X	X	X	X	X	X	
Vascoconstrictors																	X
Vitamins		X	X						X	X	X	X	X	X		X	
Hematinics		X	X														
Miscellaneous		X	X							X						X	

X - Therapy used one or more times

later course when gastrointestinal symptoms may recur. The maintenance of acid-base and electrolyte balance should be attempted also, with frequent serum pH, acid-base, and electrolyte studies as a guide.

When increasing evidence of depression of bone marrow function ensues toward the second and third weeks after exposure, certain precautions are indicated. To reduce infections, an effort to minimize bacterial exposure should be attempted, utilizing isolation and aseptic techniques in contacts with the patients. Although prophylactic antibiotics have been employed in many instances, real proof of their value for this purpose is not too clearcut. There are indications that such use may have blunted their effectiveness in subsequent infections during the course.

Bacteriocidal antibiotics in parenteral form should be reserved for therapeutic use in high dosage when infections of overt or even occult nature occur. These may be suggested by symptoms, by fever, or simply by a sharp rise in a previously low sedimentation rate, despite the absence of any resultant leucocytosis. If possible, bacterial sensitivity studies should be performed and their results used as a therapeutic guide.

Hemorrhagic phenomena are difficult to treat by any conventional means. Platelet transfusions have been tried with some possible temporary benefit resulting. Anemia, which develops insidiously, will respond to conventional transfusion therapy. This should be used only when a clinically significant fall in red cell volume has developed.

A new form of therapy may be utilized to treat severe pancytopenia accompanied by distinct clinical sequelae, such as uncontrollable infection or bleeding, with a clearly grave prognosis. This is the performance of bone marrow transplantation using cells from a homologous donor, matching in sex, and in major, and most minor blood subgroups. The time for successful performance of this procedure had previously been considered to be limited to a few days after radiation exposure. Now, the recent, apparently helpful, use of such a transplantation procedure in the Yugoslavian accident patients about a month after exposure suggests that the decision concerning its use can await the unfolding of the clinical course. This delay removes the necessity to base such action on the preliminary physical dosimetry and early, fragmentary data concerning the extent of radiation injury.

Very little is known as yet about the utility or even desirability of bone marrow transplantation in man.

In the treated Yugoslavian patients, a prompt rise to a peak occurred in the level of granulocytes, platelets, and reticulocytes before such improvement was found in a lower dose patient recovering spontaneously. Also, the pattern of platelet response was somewhat different. Furthermore, red cell agglutination tests indicated a phase of increase in the number of donor cells during the time when transfused cells would have been decreasing. However, there may be a relative and gradual recession of the hematological picture subsequently at a time when the late "immune disease" which characterized graft rejection in lower mammals might be expected.

It may prove that the donor marrow served as a temporarily functioning bridge over the hiatus in the patients' blood formation process.

What the over-all value of the transplant procedure will be cannot yet be stated. It did seem to permit survival in 3 patients who may have been expected to die - at least on the basis of doses of 600 or more rad.

Last April a group from the Health Physics Division at ORNL went to Belgrade - re-enacted the accident and made thorough and accurate dose measurements. These are summarized in Table VII.

Table VII - Yugoslavian Accident Revised Dose Estimates

Patient	Neutron (rad)		External γ	Total
	(H) nγD	Charged Part.	(rad)	(rad)
Y1 (V)*	133	89	214	436 (640)**
Y2 (D)	136	91	192	419 (500)
Y3 (M)	130	87	209	426 (580)
Y4 (G)	135	90	189	414 (600)
Y5 (H)	99	66	158	323 (420)
Y6 (B)	67	45	95	207 (350)

* Patient code in original report.

** Previous total rad dose estimate.

On the basis of these lower doses we are inclined to conclude that at best the benefit of bone marrow in these cases is highly questionable.

The question of the possibility of reversing lethal radiation effects to the bone marrow in man by transplantation of marrow remains unanswered. It should be reserved as a desperate measure against overwhelming clinical odds for seriously ill patients in Group III and above until more data become available.

In more seriously affected patients in Group III, occurrence of rather severe gastrointestinal symptomatology, including partial intestinal obstruction, may take place. A bland diet in the acute illness phase may be helpful in minimizing such difficulties.

GROUP IV - The patients in this range have run a course similar to those in the upper end of Group III, but telescoped into a shorter time period, and with a fatal outcome. Gastrointestinal difficulties require the major therapeutic effort before hematologic disturbances reach full fruition. Vigorous treatment, including

tubal gastrointestinal decompression

fluid replacement with correction of electrolyte and caloric deficits

the use of antiemetics

antihypotensive agents

antibiotics

bone marrow transplantation

are advocated in this situation.

Secondary cardiovascular and renal failure may further complicate this grave clinical state. Response to hemodialysis in one such instance was poor. Detailed biological data collection is particularly indicated in these difficult cases if present-day therapeutic inadequacy is to be altered in the future.

GROUP V - The one case in this group showed the evidence of the experimentally anticipated central nervous system injury associated with very high radiation dose. Palliation of the accompanying hypotension and gastrointestinal symptoms was carried out. No specific recommendations are yet available for this situation, other than supportive therapy.

LATE SEQUELAE - The only late sequelae of radiation overexposure in the accident cases reported herein has been the development of bilateral cataracts. There is no known prophylaxis against this occurrence, but if the usual spontaneous regression of the radiation cataract is inadequate, the ordinary surgical procedure for its removal is satisfactory.

No other long-term effects can be anticipated specifically in any given case, although the general statistical probability of leukemogenesis, carcinogenesis, or genetic mutation may be slightly enhanced. There are no such findings reported in any of these cases.

V. CONCLUSIONS

The general medical findings in the radiation accident patients reviewed are not novel. They correspond with those reported in a number of other situations in which humans have been exposed to significant wholebody radiation overexposure. However, these particular findings stem from the types of accidents which are of special interest to an increasing number of physicians now coming into contact with the fast-growing field of nuclear technology. For this reason, conclusions drawn from this series may be especially useful.

It is rather reassuring to find that, despite the disturbing physical complexity of nuclear criticality accidents, the key procedures for clinical evaluation of resultant injury are such familiar ones as

a detailed medical history
thorough physical examinations
and accurate blood counts.

The additional support provided by improvements in radiation dosimetry and modern clinical laboratory procedures is, of course, very helpful as well.

In the therapy of such patients also, good medical management, firmly based on an understanding of the pathophysiology of the acute radiation syndrome, does not really differ from the treatment of less modern maladies. The development of bone marrow transplantation as a possible specific form of treatment for this syndrome may provide, however, a somewhat specialized therapeutic procedure.

Concerning the relative value of physical dose measurements and biological signs of injury as aids in the care of human radiation overexposure, the nature of the exposure incident is most important. What is suited to the triage of victims of a nuclear warfare catastrophe is not necessarily appropriate for the industrial accident victim. The utilization of precise clinical observations and frequent laboratory tests as advocated herein, with calculation of the injury profile score, may not be feasible under other circumstances. However, it is considered to be of particular value, especially when supplemented with good mixed radiation dosimetry, in medical management of the accidents of nuclear technology.

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